# Contrast sensitivity and glare: new measurement techniques and the visual consequences of wearing head-mounted displays

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# Abstract

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**Contrast sensitivity and glare: new measurement techniques and the visual consequences of wearing head-mounted displays**

Key words: contrast sensitivity, disability glare, binocular summation, binocular inhibition, Google Glass

The main aim of this thesis was to evaluate the performance of the contrast sensitivity clock (CSC), a new screening device for measuring contrast sensitivity (CS) and glare. This device allows CS without glare, with glare and disability glare scores to be recorded.

After initial data collection the design of the CSC was slightly amended improving the performance of the device. The amended design of the CSC was shown to be a valid, discriminative and repeatable measure for purpose. The CSC is also a quick test to perform and is relatively cheap to produce. If all these factors are considered it shows potential to become the test of choice for the assessment of visual glare.

A head-mounted display system was also evaluated in terms of the glare effects it may cause. The monocular display screen of the device significantly reduced the CS of the eye directly exposed but also had an effect on binocular performance, reducing amounts of binocular summation.

Electronic devices, including head-mounted displays and satellite navigation systems can seriously affect CS at low luminance levels, similar to those found when driving at night.

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# 1.0 Introduction

The main aim of this study was to evaluate and further develop the contrast sensitivity clock (CSC), a simple device quantifying how disability glare (DG) affects contrast sensitivity (CS). The CSC was initially designed to assess how glare affects visual function in a quick and inexpensive format that eliminated some of the design flaws found in some earlier glare testers (Elliott and Bullimore 1993). Driving at night is one of the more serious conditions where a reduction in visual performance caused by glare could have serious ramifications. In 2009 there was an amendment to a European directive (2009/113/EEC, Brussels 2009) which promoted greatly enhanced levels of visual assessment by competent clinicians when assessing driving ability. One of the areas to be given more attention was that of CS and glare. Despite this directive neither of these visual functions is routinely tested as part of the UK's driving standards assessment.

Research has been able to comprehensively show that the elderly intra-ocular lens scatters more light than in the younger population, something which can be greatly exaggerated with the presence of cataract (Elliott and Bullimore 1993; van den Berg 1995; Vos 2003a; van Rijn et al. 2005; Babizhayev et al. 2009; van den Berg et al. 2013). This thesis attempts to evaluate the suitability of the CSC at distinguishing between those expected to have impaired visual performance in the presence of glare and the normal population. A conclusion will be made commenting on the suitability of the CSC for potential use in the driving standards process and an appropriate pass/fail level for the device will be discussed. For this reason participants were chosen who had visual acuity

(VA) within or very close to the UK standard for driving (see chapter 4) and testing was carried out binocularly, the natural condition when driving a vehicle. This is not to say this is the sole purpose of the CSC. Although not discussed here, the device could also potentially be used as an indicator for cataract surgeries or other clinical requirements where vision under the influence of glare needs to be examined.

Two commercially available devices - Google Glass (Google Inc.) and a TomTom sat-nav were also used in order to investigate how CS could be reduced by the display screens of these devices, particularly under low luminance conditions.

In the subsequent chapters of this thesis the fundamentals of CS and glare will be explained (chapter 2). The changes to the ocular media that may influence the amount of intra-ocular scatter will be described (chapter 3). How reduced visual function relates to deficits in driving performance will be discussed (chapter 4). A review of both past and present glare testers takes place in chapter 5 before the experimental chapters are thoroughly presented in chapters 6-9.

# 2.0 Contrast sensitivity and glare

## 2.1 Contrast sensitivity

CS is one of the most useful ways to assess a person's vision in the real world. Patients may retain good acuity and yet complain of poor vision if their CS is reduced (Bernth - Petersen 1981; Koch 1989; Elliott et al. 1990a).

Contrast is a measure of the amount of lightness or darkness an object has in relation to its background and can be specified as Weber contrast:

$$\frac{L_{max} - L_{min}}{L_{background}}$$

Michelson contrast:

$$\frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

Or root mean squared (RMS) contrast:

$$\frac{L_{\sigma}}{L_{\mu}}$$

Where $L_{max}$, $L_{min}$, $L_{background}$, $L_{\mu}$ and $L_{\sigma}$ are luminance maximum, minimum, background, mean and standard deviation respectively. Weber contrast is preferred for letter stimuli, Michelson contrast for gratings and RMS contrast for natural stimuli (Pelli and Bex 2013).

The term 'high contrast' refers to a situation where the difference in luminance between the background and stimulus is large. The term 'low contrast' indicates a situation where there is little difference in luminance between the stimulus and background (see figure 2.1). The contrast threshold of an individual is the minimum contrast, just noticeable by the observer.

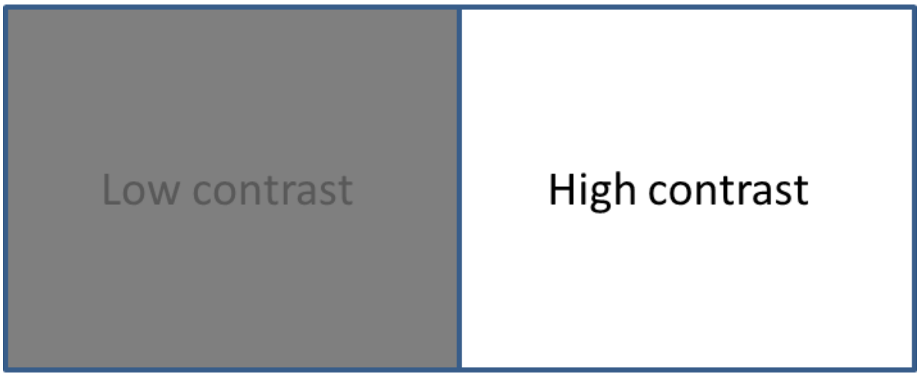



Figure 2.1 showing high and low contrast. On the left, the background of the square and the letters are of similar luminance making the letters harder to see (low contrast difference between the background and the stimuli). On the right there is a large luminance difference between the background and the words meaning the letters stand out much more clearly (high contrast difference between the background and the stimuli).

The ability to see small objects at very high contrast is well represented by recording a person's VA. This measurement however does not give us any information of the patient's ability to see larger objects at lower contrast, a more realistic assessment of the visual world (Koch 1989; Elliott et al. 1990a). The contrast sensitivity function or CSF gives a more complete description of the visual system as VA levels can remain normal in individuals where peak CS is reduced (Pelli and Bex 2013). The CSF represents the relationship between CS and spatial frequency (Watson and Ahumada 2005).

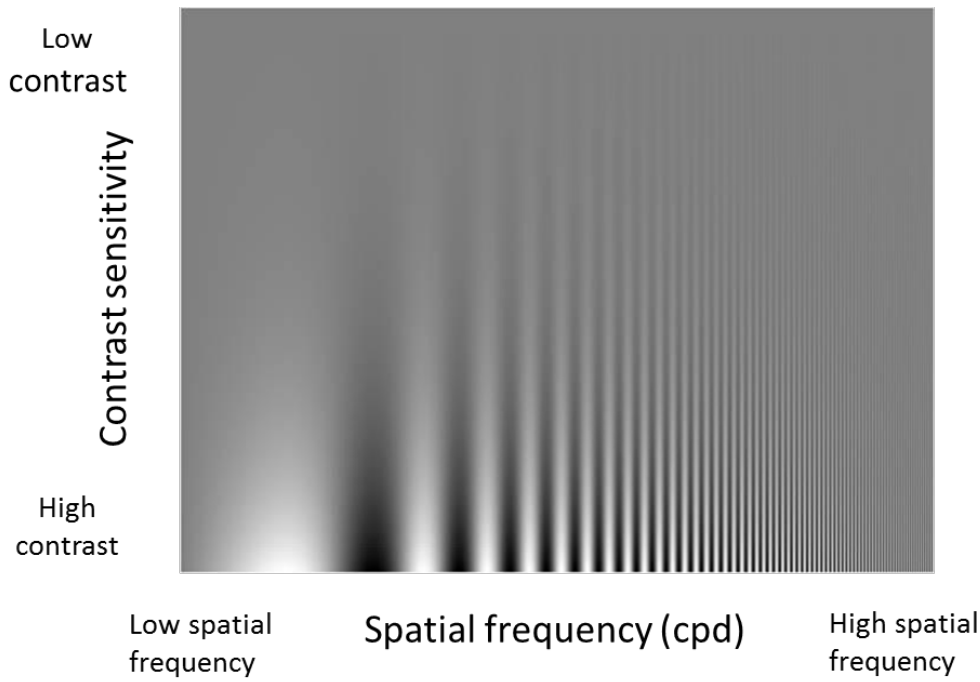



Figure 2.2 showing how CS relates to spatial frequency. This figure shows contrast/CS (y axis) against spatial frequency (x axis). CS is the reciprocal of contrast threshold. Contrast is the same at any level of the figure for all spatial frequencies. The sine wave grating that is visible to an individual represents their own CSF. Maximum CS is normally found for medium spatial frequencies (3-6cpd).

In a sine wave grating the part of the wave incorporating 1 maxima (highest luminance) and 1 minima (lowest luminance) is classed as a cycle. The number of adjacent dark and light lines (cycles) within a defined visual angle is called the spatial frequency and is given by the units cycles per degree (cpd). High spatial frequencies have many adjacent lines in a defined visual angle, low spatial frequencies the opposite (see figure 2.2).

Image removed due to copyright laws

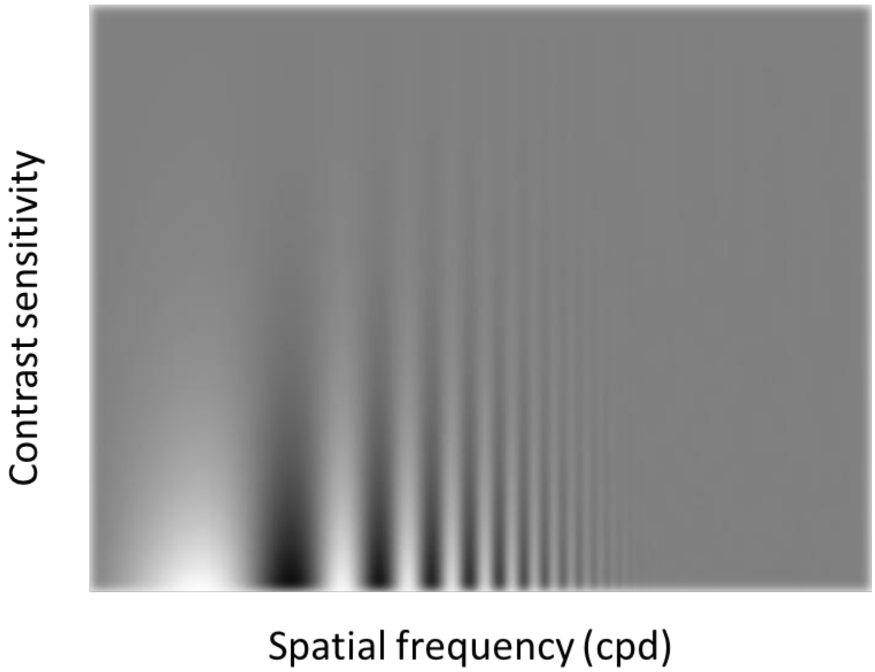
This image showed an example of the CSF and can be found in the paper referenced below

Figure 2.3 showing the mean CSF for 14 young and 14 older participants (Casco et al. 2011).

When a 3° to 6° visual field is used, CS is at a maximum for gratings of around 4cpd (Campbell and Green 1965b; Campbell and Robson 1968; Levi and Harwerth 1977; Thomas 1978). A peak as high as 10cpd has been observed when a 1° foveal field size was used (Hoekstra et al. 1974; Sjostrand 1978) and a maximum of 1cpd when an eccentric viewed target was used (Rovamo and Virsu 1979). These results indicate that eccentricity plays a big role in the CSF of an individual. Maximum CS also shifts to lower spatial frequencies when luminance decreases (Kulikowski 1971).

Peak CS is normally found at spatial frequencies of 3-6cpd. This range has been shown to be the most important feature of CSF for prediction of visual performance in everyday tasks such as reading, driving and mobility (Marron and Bailey 1982; Legge et al. 1985; Woods and Wood 1995).

Campbell and Green (1965b) found that at spatial frequencies above the peak of the CSF curve that there is an exponential decrease in CS with increasing spatial frequency. Optical blur particularly affects high spatial frequencies. The diagram below shows a blurred version of figure 2.2.




Figures 2.4 shows how optical blur affects CSF. The figure has been subjected to a low-pass filter. High spatial frequencies are now much harder to visualise.

There are a number of reasons why CS should change with the ageing process. Age-related pupil miosis, lenticular absorption and backward light scatter all lead to a drop in retinal illuminance which has been shown to impact on CS at higher spatial frequencies (Kelly 1972). It has been estimated that the eye of a 20 year old transmits approximately 3 times the light of a 60 year old (Weale 1963). Increase light scatter would be expected to cause a reduction in CS at all spatial frequencies (Wolf and Gardiner 1965). As well as optical changes there are also significant neural changes as we get older. A loss of retinal neurones with age is seen (Gartner and Henkind 1981), a build-up of lipofuscin (an ‘age pigment' that builds up in cells during the ageing process) in the retinal pigment epithelium as well as cell loss and lipofuscin build-up in the lateral geniculate bodies and cortex (Spear 1993). There is a 54% cell loss between the ages of 20 and 87 in the striate cortex (Devaney and Johnson 1980).

Studies investigating CSF changes with age have found conflicting results. Arden and Jacobson (1978) found no change with age. Sekuler et al. (1980) found age to affect low and medium spatial frequencies although this finding was later refuted in a follow up study. The reasons for the original findings were likely due to the use of a small participant sample size, possible optical blur from habitual spectacle correction and insufficient participant screening for certain ocular pathologies (Owsley et al. 1983). Ageing has also been shown to reduce CS across all spatial frequencies (Skalka 1980; Ross et al. 1985). There is however the most support for ageing affecting CSF at medium to high spatial frequencies (Derefeldt et al. 1979; McGrath and Morrison 1981; Owsley et al. 1983; Owsley et al. 1985; Elliott 1987) the latter of which attempted to overcome some of the inaccuracies of earlier reports including the use of optimum optical correction and screening for ocular disorders.

Cataractous changes in the eye complicate matters further. In participants with very early cataract, measuring CS at low spatial frequencies has been found by some to be of little value (Chylack et al. 1993a). As is the case with the older population, testing at medium to high frequencies was found most useful (Chylack et al. 1993a; Elliott and Situ 1998). Studies that have suggested low spatial frequencies are useful when examining cataract patients have generally used participants with more advanced lens changes (Hess and Woo 1978; Elliott et al. 1989; Drews-Bankiewicz et al. 1992). Testing at low spatial frequencies, as with the use of the Pelli-Robson chart at 1m, is likely to be of value in people with more advanced cataract (Elliott and Hurst 1990; Lasa et al. 1992; Rubin et al. 1993).

### 2.3 Spatial frequency channels

Campbell (1979) suggested that the visual system acts according to Fourier principles and that sinusoidal information of an image is transmitted through neural channels called spatial frequency channels. Fourier principles are where any waveform can be shown as the sum of a number of sine waves, of specific phase and amplitude.

Adaptation of these spatial frequency channels can occur which renders them less sensitive to subsequent stimulation of the same channel for a certain period of time. This adaptation is similar in many respects to adaptation of the photoreceptors to light. Information about how many spatial frequency channels are responsible for the human CSF can be estimated by these adaptation studies (Blakemore and Campbell 1969).

If at one extreme the CSF reflected the sensitivity of one single channel then the adaptation of this single channel should affect the sensitivity of all spatial frequencies. On the other hand, if there are many spatial frequency channels, then adaptation to one of these channels should only affect sensitivity to one particular frequency. In actual fact, adaptation of a single channel affects sensitivity to that frequency and a limited range of surrounding frequencies (Blakemore and Campbell 1969).

Watson and Robson (1981) estimated that there were seven selective mechanisms or channels by investigating the difference between numerous pairs of spatial frequencies. Different studies produce different estimates between the number, the size and the shape of the spatial frequency channels. The average shows between six and eight spatial frequency channels present. A channel which responds to say 8cpd would at 6 and 10cpd respond with a reduced value. The spatial frequency channels can be thought of as filters which have the effect of selectively attenuating any component of specific frequencies. The CSF is the sum of these filters. Such findings led to the development of clinical tests estimating the CSF at certain spatial frequencies in order to assess these channels (Ginsburg 1984). The Vistech MCT-8000 and the CSV 1000E (both discussed in more detail in chapter 5) were developed to measure CSF at five different spatial frequencies to assess five of these channels.

### 2.4 Threshold

In order to measure a person's CSF the minimum detectable contrast is found for a number of spatial frequencies. Sensitivity is the inverse of contrast threshold and in order to calculate an individual's CSF, CS is plotted against spatial frequency. One of the main problems with finding contrast threshold is defining what is actually defined as minimally detectable. It is not wholly correct to assume that there is a certain contrast above which everything is seen and below which everything is missed.

The way sensitivity is normally found is by showing many repetitions at each contrast level, and then plotting the percentage of the detected stimuli as a function of contrast. This results in a characteristic sigmoid shape plot (figure 2.5).

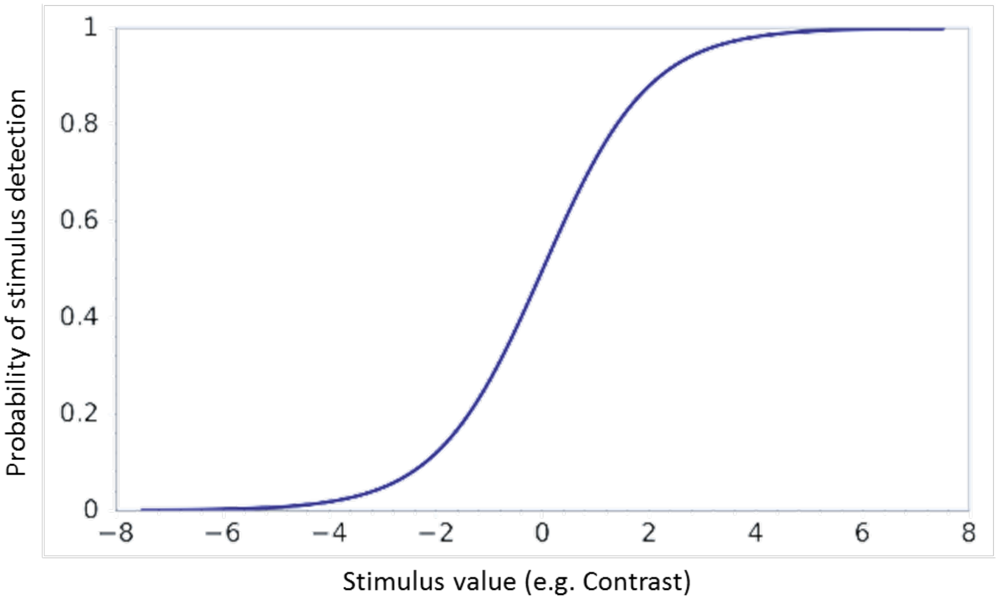



Figure 2.5 showing the sigmoid shape plot obtained from a typical psychometric function. The psychometric function is used to explore the threshold region of stimulus detection, where successful responses become probabilistic. The far right of the figure indicates 100% successful responses and the far left 0%.

The problem with this method is that it is dependent on patient responses and if someone was just to keep on saying that they had seen the stimulus, even if they had not, it would result in a 100% correct response leading to the results being very unreliable. Therefore reliable tests for measuring CS require a method to counteract guessing. One possible way round this is to use forced-choice methods. For instance you could have a screen split into two, with stimuli shown on either side and then ask the patient if the stimulus was seen on the right or the left. This is called a two-alternative, forced-choice method (2-AFC). This would mean that guessing would lead to a correct response just 50% of the time. Next a CSF curve would be generated for each frequency using a point normally at an estimate of 75% correct responses. A point at 75% is used because it is half way between 50% (chance) and 100%. However this process can be very time consuming as it uses many trials which lie a long way from the 75% point.

In an attempt to speed up testing the staircase method was developed. This involves using a forced-choice method of testing but this time, if a correct response is recorded, the CS is lowered and repeated. With every incorrect response it is partially raised and repeated (Cornsweet 1962).

Figure 2.6 below gives a visual representation of a basic staircase method:

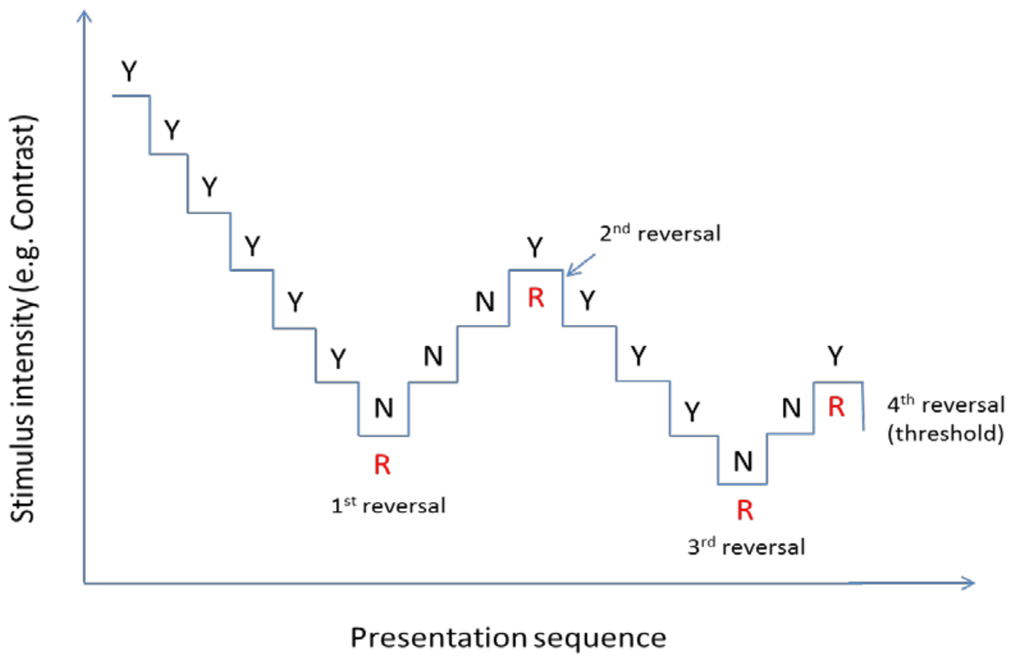



Figure 2.6 showing an example of a staircase method used to find contrast threshold. Initial stimulus intensity is normally high so that it is easily seen by the participant. Stimulus intensity is decreased until a target is incorrectly identified, at which point the stimulus intensity increases until the next target is correctly identified. Contrast threshold is normally given after a number of reversals, in this case four. Y is a correctly identified target, N is an incorrectly identified target and R shows a reversal in stimulus intensity.

There are various versions of this, some requiring two or three correct responses at a certain contrast level before being lowered. The staircase method is faster as it converges around threshold so you don't 'waste' meaningless trials, normally starting above threshold to give initial encouragement to the observer. A threshold estimate is normally given after a fixed number of reversals (a reversal being a correct response followed by an incorrect response), normally discounting the first few to avoid errors caused by the uncertain starting point.

The Pelli-Robson chart has been developed more recently for testing CS. The key difference is that it uses letters instead of sine wave gratings as a target. This consists of triplets of letters that progressively reduce in contrast via a geometric progression, therefore using the descending method of limits. This is another psychophysical technique where the initial stimuli are at high contrast and are therefore easily recognisable by the participant. As testing continues the letters gradually reduce in contrast until they are no longer correctly identifiable. Each triplet of letters carries a score of 0.15 log units and single letter scoring can be achieved with each letter scoring 0.05 log units (Elliott et al. 1991a).

Pelli and Robson (1991) stated that the right hand side (high spatial frequency end) of the CSF of normal and low vision observers can be well estimated by using high contrast VA measures. The Pelli-Robson chart was therefore designed to concentrate on CS testing at low spatial frequency, using letters of 1-2cpd at a viewing distance of 1m. This is therefore tailored more to a clinical testing environment as high contrast VA is recorded during any normal eye test. The use of letters also gives a multiple forced-choice method. As far as the patient is concerned any letter based test is a 26AFC method. This means the test is much less prone to guessing than a 2AFC method meaning a number of reversals are not required. If the patient responds correctly you can be pretty certain that they have not guessed. Although to the patient there are 26 alternatives, the test itself actually only uses 10 different letters C, D, H, K, N, O, R, S, V and Z.

Many CS tests are now available each with their own advantages and disadvantages. The Pelli-Robson chart is both easy to use and results have been shown to be reliable (Rubin 1988; Elliott and Bullimore 1993). However care should be taken as results could be influenced by lighting, reflections and fading of charts which can alter the contrast of the letters seen (Woo and Bohnsack 1986).

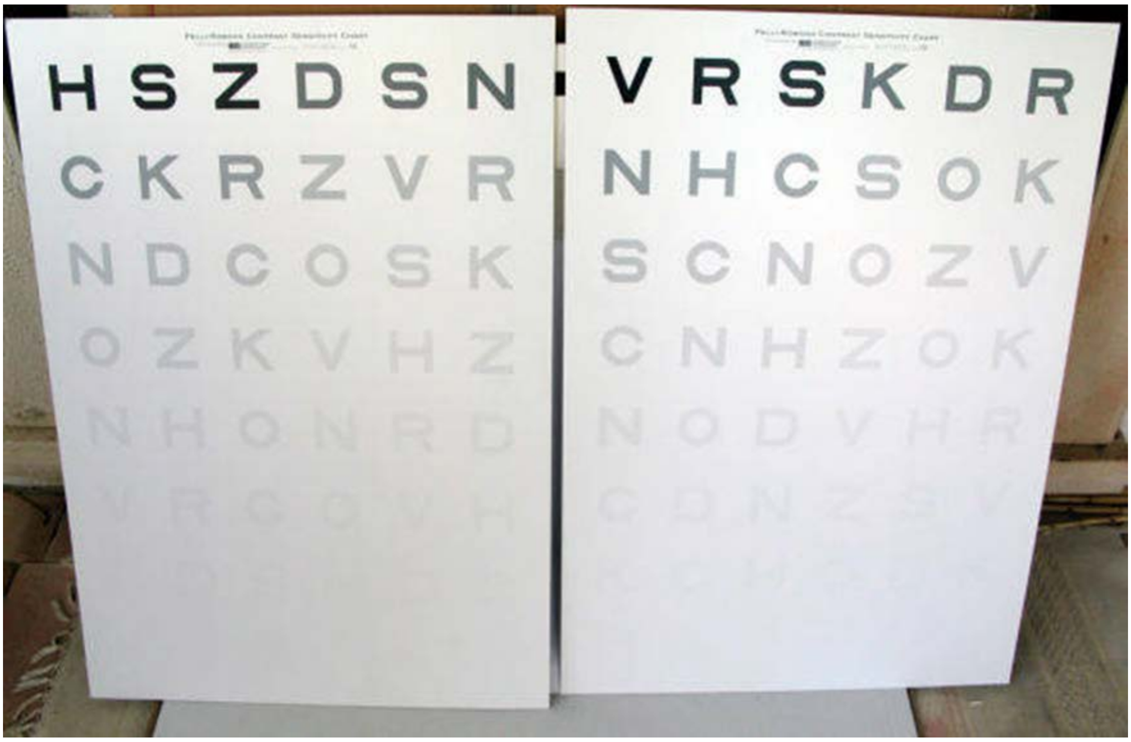



Figure 2.7 showing the Pelli-Robson CS chart.

Tests which use gratings eliminate the confounding factors of language and intelligence from their results but tend to have poor reliability (Richman et al. 2013) as they are more prone to guessing. It is important that a CS test be both discriminative and repeatable. Therefore an ideal CS test would give an accurate estimate of the CSF and be reliable (Richman et al. 2013).

Pelli and Bex (2013) stated that any test recording CS should be forced-choice therefore minimizing the effects of attitude, have many alternatives to minimise guessing and speed up threshold estimates and present one letter at a time, negating the effects of crowding.

### 2.5 Binocular summation and inhibition

When it comes to measuring CS there has been some debate whether measurement would be best done binocularly or monocularly when assessing participants with uni-ocular cataract or in anyone where there is a difference between the two eyes in terms of visual performance. It is well established that when the sensitivities of the two eyes are equal the binocular performance is superior to that of the monocular (Pardhan 1993; Pardhan 1996; Plainis et al. 2011). This is known as binocular summation and has been observed when measuring VA and CS (Blake and Fox 1973; Blake et al. 1981; Plainis et al. 2011). The widely accepted value for this summation effect is a $\sqrt{2}$ increase in binocular performance over the monocular for CS (Campbell and Green 1965a; Blake et al. 1981; Legge and Rubin 1981). This effect is not as large when it comes to measures of VA, where a binocular summation effect of between 5-13% has been observed (Horowitz 1949; Home 1978; Heravian et al. 1990; Pointer 2008). As the difference in visual performance between the two eyes increases the effects of binocular summation decrease until a point is reached where binocular performance is equal to the monocular performance of the better eye (Pardhan et al. 1990). If this difference between the two eyes continues to increase would the binocular performance remain at the visual performance level of the better eye or decrease still further?

If we look to monovision in presbyopic contact lens patients, where one eye is used for distance vision and the other used for near, studies demonstrate that even when the image of one eye is degraded binocular vision can be dominated by the unaffected eye (Evans 2007). It has previously been shown that binocular VA could be well inferred by the VA in the better eye (Mangione et al. 1992). This may lead us to the conclusion that monocular testing of visual performance would be most useful. However there is much evidence to suggest otherwise due to a process known as binocular inhibition (Blake and Fox 1973; Gilchrist and Pardhan 1987), where binocular visual performance is significantly worse than either eye on its own. This has been shown to occur when there is a significant difference between the two eyes either by way of monocular blur (Pardhan and Gilchrist 1990b), monocular glare (Pardhan and Gilchrist 1990a), monocular cataract (Pardhan and Gilchrist 1991) or a difference in luminance between the two eyes (Fechner 1860; Gilchrist and Pardhan 1987). For this reason it is important to measure both monocular and binocular CS in participants who have a difference in visual performance between the two eyes. When assessing the impact of cataract and glare on CS, it would appear important to measure the visual performance binocularly if the task involved is a binocular task.

## 2.6 CS and glare

Glare is an additional problem in patients with cataract, those who have refractive surgery complications and in people with other media changes. Efforts have been made to quantify the amount of CS impairment from a glare source and most solutions tend to compare an individual's baseline CS measures with CS under the influence of glare (Elliott and Bullimore 1993; van Rijn et al. 2005). In young healthy observers it has been shown that the veil of light caused by a glare source is made up of roughly equal contributions from the cornea, lens and fundus (Vos 2003a).

## 2.7 What is glare?

The word 'glare' is a broad term that can used to describe a number of different effects. In lay terms, glare can be described as an excess of light having a detrimental effect on vision (Vos 2003b). There are a few basic terms that are useful when discussing the term glare (Mace et al. 2001):

**Brightness** is a relative term that describes whether an object appears to emit more or less light to the observer.

**A point light source** is a light source that subtends a very small angle at the observer's eye meaning its attributes are not affected by size only its luminous intensity.

**Luminous intensity** is a measure of the strength of visible light given off by a point source in a given direction, normally measured in candelas (cd).

**Luminance** is a physical measure of the amount of light reflected or emitted from a surface and does not vary with distance. It is normally measured in candelas per square metre ($cd/m^2$).

**Illuminance** is the amount of light at any given point on a surface. Illuminance is related to the luminance of the light source by way of the inverse square law and is therefore very much dependant on distance, measured in lux (lumens per square metre). Retinal illuminance is the amount of light reaching the retina, normally measured in trolands (Td). The retinal illuminance is calculated by multiplying the Luminance entering the eye in $cd/m^2$ by the pupil area in $mm^2$.

Glare found its way into scientific literature when Gaster (1910) asked the question, why is glare incapacitating for some people yet well tolerated by others in similar environments? At about the same time Parsons (1910) discussed a glare scale, ranging from the discomfort caused by temporary scotomas to permanent light damage. At this time the theory of glare was a highly unstructured domain classed as more or less discomfort. This remained more or less the same until Stiles (1929) proposed a change from using the general term glare identifying a recognisable and measurable aspect, namely the masking effect of a glare source in one part of the visual field on the quality of vision in another. He proposed naming this phenomenon ‘Disability Glare’, grouping all other aspects under the heading of discomfort glare. His proposal was widely accepted and is still widely used to this day.

## 2.8 Discomfort glare

Discomfort glare occurs when the brightness of the visual field is suddenly higher than that of the level to which the eye is already adapted, either via a direct light source or one that is reflected from another surface (Mace et al. 2001). This bright light causes a level of subjective discomfort or annoyance (Mace et al. 2001). Others have further divided this category of glare, defining discomfort glare as the distraction effect of peripheral light sources on the field of view and dazzling glare as the way a bright light source makes someone screw up their eyes and reach for their sunglasses (Vos 2003b). Discomfort glare is sometimes measured on a subjective scale called the De Boer scale (De Boer 1967).

| **Rating** | **Visual response** |
|---|---|
| 9 | Unnoticeable |
| 8 | |
| 7 | Satisfactory |
| 6 | |
| 5 | Just admissible |
| 4 | |
| 3 | Disturbing |
| 2 | |
| 1 | Unbearable |

Table 2.1 showing the De Boer rating scale for discomfort glare.

The amount of discomfort glare experienced is normally influenced by the location of the glare source relative to the line of sight, the luminance of the background (Mace et al. 2001) and the illuminance at the eye (Flannagan 1999; Bullough et al. 2004). The chromaticity of the glare source has also been shown to have an effect. As early as the 1930’s it was reported that blue light produced more discomfort glare than yellow light (Bouma 1936) and more recently monochromatic, highly saturated colours have shown that yellow sources are perceived as less glaring (from a visual comfort perspective) than green or blue sources (Bullough et al. 2001). The new high intensity discharge headlights (HID) have a blue hue due the wavelength of light they transmit. They have been found to generate a higher discomfort glare rating than normal halogen bulbs although this is not translated to increased DG effects (Bullough et al. 2002).

The age of a person is another factor which may have an influence on the amount of glare perceived due to normal ageing changes in the eye. Studies investigating the effects of age on discomfort glare have found mixed results. Olson and Sivak (1984) concluded that the older population suffered more from the effects of discomfort glare than the younger population. However studies by Tsongos and Schwab (1970) and Theeuwes et al. (1996) both found younger people to be more affected . Psychological factors, expectations or even glare experience could go some way to explaining these differences.

## 2.9 Disability glare

DG is sometimes termed glare sensitivity (Rubin et al. 2007; Owsley and McGwin 2010) and is caused by intraocular light scatter (straylight) which spreads a veil of light across the retina, reducing the contrast of the retinal image, making objects harder to see (Allen and Vos 1967; Vos 1984; IJspeert et al. 1990; Elliott and Bullimore 1993; van den Berg 1995; Vos 2003b). This is an optical phenomenon caused by light scatter in the media of the eye. DG tends to increase with age and further so with cataract (Elliott and Bullimore 1993; van den Berg et al. 2013). A value for DG is normally determined by measuring CS under both normal and under glare conditions, the difference between these two measures giving a value for DG. DG is normally measured in log units (logCS without glare – logCS with glare).

Although an image may be sharply focused on the retina, the presence of an additional light source flooding the retina will lower the contrast of the scene. This effect of flooding the image with light affecting the retinal image clarity is called DG. Holladay (1927) published the first data on the masking effect of a halo observed around a glare source and this was defined as the equivalent veiling luminance ($L_{eq}$) that would produce the same masking effect. Vos et al. (1976) identified that intraocular light scatter was producing this veil of light and by using a glare source was able to quantify this equivalent veiling effect. Paulsson and Sjostrand (1980) combined a quantitative assessment of intraocular light scatter with contrast measure to derive an expression for light scattering factor (LSF);

$$LSF = L/E({}^{M_2}/_{M_1} - 1)$$

Where L = luminance of target

E = direct luminance onto the eye of the glare light

$M_2$ = detection contrast threshold with glare light

$M_1$ = detection contrast threshold without glare light

This gives a direct measure of intraocular light scatter. Contrast was measured using a cathode-ray tube with and without a glare source. This gave an idea of the reduction in CSF caused by the glare source. In this study five normal patients aged 30-61 years were used as well as six patients with posterior sub-capsular cataract aged 46-68 years. In the control group the glare source showed no significant effect on CS. However there was a marked reduction in CSF with glare in the group with cataract. This contrast loss was more noticeable at low and medium spatial frequencies. LSF was also found to differ in cataract patients with the same VA. Paulsson and Sjostrand (1980) summarised that this could become a useful clinical vision test to measure DG.

An equation for DG can be shown by re-arrangement of the Paulsson and Sjostrand equation above:

$$LSF = L/E({}^{M_2}/_{M_1} - 1)$$

Where $M_1$ is contrast threshold without glare, $M_2$ is contrast threshold with glare

Rearranging, ${}^{M_2}/_{M_1} = \left({}^{(LSF \times E)}/_{L_s}\right) + 1$

But the definition of LSF is the proportion of ocular illuminance E that turns into veiling luminance $L_v$

Hence $LSF \times E = L_v$

And contrast sensitivity $CS = \log({}^{1}/_{M})$

Rearranging, $M = {}^{1}/_{10^{CS}}$

Substituting into equation $M_2/_{M_1} = \left((LSF \times E)/_{L_s}\right) + 1$ gives,

$$10^{CS_1}/_{10^{CS_2}} = \left(L_v/_{L_s}\right) + 1$$

Expanding

$$10^{(CS_1 - CS_2)} = \left(L_v/_{L_s}\right) + 1$$

But $CS_1$-$CS_2$ is disability glare (difference between CS without and with glare)

Hence $10^{DG} = \left(L_v/_{L_s}\right) + 1$

Hence, finally

$$DG = \log\left(\left(L_v/_{L_s}\right) + 1\right)$$

Where $L_V$ is the veiling luminance caused by light from a glare source scattered by the ocular media and $L_S$ is the mean luminance of the stimulus being observed (Steen et al. 1993).

Veiling luminance can be best explained when thinking of a projector screen in a lecture theatre. In such a case the room lights are often dimmed or turned off, particularly those in the immediate vicinity of the screen. This is because the lights produce a veiling luminance over the screen, reducing its contrast and making it harder for the audience to see. This can be applied to the eye by thinking of the room lights as the intraocular light scatter and the projector screen as the retina.

One of the most dangerous tasks we undertake where DG can be a real issue is when driving at night. If a scenario is considered where a motorist is driving down a country road, there is a pedestrian at the side of the road and an oncoming car has its own headlights on. During the daytime the luminance of the pedestrian ($L_s$) is much higher than the veiling luminance caused by the headlights of the oncoming car ($L_v$), DG effects are small and the pedestrian is easy to spot. Things change dramatically when the same scene is considered at night. In this situation the luminance of the pedestrian is much lower than the veiling luminance produced via the car headlights meaning the amount of DG is very large and the pedestrian could be rendered invisible. DG glare is therefore of great importance when assessing the ability to perform certain tasks.

## 2.10 Photostress recovery time

Photostress occurs when a person observes a very bright light source like a penlight or encounters an even more intense light flash from a camera or laser (Severin et al. 1963; Glaser et al. 1977). Here the light bleaches rod and cone photo-pigments, reducing retinal sensitivity and producing afterimages. These photo-pigments regenerate slowly over many seconds (Severin et al. 1963; Glaser et al. 1977).

The time taken for the photo-pigments to fully regenerate is given the term photostress recovery time. The speed at which the visual system recovers is largely dependent on the integrity of the photoreceptors and the retinal pigment epithelium. Photostress recovery time increases with age, doubling from 10 seconds to 20 seconds between the ages of 10 and 70 (Elliott and Whitaker 1991). Other ocular pathology such as diabetic retinopathy, macular oedema and age-related macular degeneration can all have an impact on the time taken for recovery, ranging anywhere from seven seconds in the normal population to 335 seconds in those with macular degeneration (Wu et al. 1990). Photostress recovery time is normally quantified as the time taken for a measure of visual function, normally VA, to return to the level reached before light exposure (Wu et al. 1990; Elliott and Whitaker 1991).

# 3.0 Sources of intraocular light scatter

## 3.1 Introduction

Chapter 2 attempted to explain how glare can affect measures of visual function; particularly CS. The following chapter will attempt to describe the sources of intraocular light scatter, produced when the light from a glare source enters the eye. This is done in a logical order from the front of the eye and the cornea through to the fundus. The majority of intraocular scatter produced by the young healthy eye was previously shown to arise in roughly equal proportions from the cornea, lens and fundus (Vos 1963; Vos and Boogaard 1963; Vos 2003a). When pathology such as cataract is present, a greater amount of light scatter is produced by the lens (van Rijn et al. 2005; Babizhayev et al. 2009; van den Berg et al. 2009b).

The different types of light scatter will also be highlighted, the theories of Rayleigh and Mie scattering explained and the relationship between veiling luminance, glare source illuminance and angle examined.

## 3.2 Cornea

As light from any glare source enters the eye the first structure it reaches is the cornea. The anterior surface of the cornea is the corneal epithelium which has a thickness of approximately 53µm (Reinstein et al. 2008). The cells of the epithelium are held together by desmosomes, resulting in minimal spacing, promoting a consistent refractive index and reducing light scatter. If spaces between cells were larger, the refractive index of the cornea would be less consistent. When light enters a medium of a different refractive index it can be left unaffected but can also be refracted, absorbed, reflected or scattered (Freegard 1997). Therefore maintaining a consistent refractive index is the best way to reduce these effects. Cells contain a number of structures, including a plasma membrane, nucleus, mitochondria, large protein aggregates and glycogen granules (Moller-Pedersen 2004). The refractive errors of these structures are not known but it would be expected that all would lead to a significant amount of light scatter within the cells (Jester 2008). In addition to this intracellular scattering, keratocytes are also present in a high refractive index collagen matrix. The collagen fibres are separated by the size of the keratocyte cell body, anywhere between 200-600nm (Muller et al. 1995). In theory this spacing would lead to a large amount of light scatter (Jester 2008) but the lack of scattering detected in the epithelium would mean the fluctuation of refractive index is minimised (Jester 2008). The transparency of the epithelium can be seen when using the slit lamp. If fluorescein is used the clear space between the fluorescein staining of the tear film and the stroma is the epithelium.

The stroma accounts for around 90% of the corneal thickness and gives the cornea its strength. It manages to transmit light because of its very regular structure and the absence of any blood vessels. The stroma consists of approximately 200 lamellae of collagen fibrils (n=1.555) embedded in a matrix of mucopolysaccharides (n=1.345) (Maurice 1957). The fibril diameters are of regular size when at the same depth of the stroma but they vary from an average of 19nm anteriorly to 34nm posteriorly (Jakus 1962). More than 90% of visible light is transmitted through the cornea (Moller-Pedersen 2004) but a small amount of back scattered light is still visible with the use of slit lamp bio-microscopy (Boettner and Wolter 1962).

Maurice (1957) calculated that if each collagen fibre scattered light independently of each other more than 90% of the incident light would be scattered, hence the stroma would be opaque and similar to the sclera of the eye. As mentioned above the cornea has a uniform arrangement of collagen fibrils of very consistent size and spacing, unlike that of collagen in other tissue. This helped Maurice devise the 'lattice theory' of light scatter, where the size (32nm) and equal spacing (64nm) of collagen fibrils in the cornea gave rise to the idea of a regular lattice. This lattice is arranged in such a way that it leads to lateral light scatter by individual fibrils. This light scatter along with light scatter from neighbouring fibrils produces destructive interference, leading to a forward transmission of light and reducing the amount of scattered light.

Later, Goldman and Benedek (1967) and Benedek (1971) modified the lattice theory to include fluctuations of refractive index as a function of distance (Jester 2008). This theory differed to that of the 'lattice theory' in that the spacing between fibrils did not have to be quite as regular as the perfect lattice described by Maurice (Benedek 1971). It was shown that if the distance between collagen fibrils was less than ½ the wavelength of visible light then destructive interference of the scattered light would leave the media clear, however if distance between fibrils was greater than this, significant scattering would be observed.

More recently, Hillenaar et al. (2011b) looked at In vivo confocal microscopy to assess backscatter from the cornea. This is an optical technique which allows minute structures in the order of micrometres to be visualised. Endothelial cell density, analysis of corneal and intracorneal thickness, assessment of cellular morphology and histopathologic changes (Moller-Pedersen et al. 1997) as well as corneal backscatter can be measured. Corneal backscatter measured by this technique is based on measurements of image intensity composed of backscatter and reflectance (Patel et al. 2007; Erie et al. 2009). Reflected light maintains the same polarization of the light source whereas scattered light does not. This allows for discrimination of the two using cross polarization (Lohmann et al. 1992).

Backscatter analysis can be used in the assessment of corneal hydration (Morishige et al. 2009), quantification of the effects of diabetes (Morishige et al. 2001; Takahashi et al. 2007) and contact lens wear (Nagel et al. 1996; Patel et al. 2002). However as high magnification is used by in vivo confocal microscopy only a very small portion of the cornea is imaged (Hillenaar et al. 2009). This means there is only a moderate positional repeatability in the paracentral and peripheral corneal regions, limiting backscatter analysis to a miniscule area of the central cornea. This reduces its usefulness in follow up assessments of certain corneal opacities.

Hillenaar et al. (2011a) used in vivo confocal microscopy to analyse the effects of sex, age and time of measurement on corneal backscatter. It was found that the mean corneal backscatter in men was 3.5% higher than that for women. In regards to age, backscatter from the anterior stroma increased slightly up to the age of 50 years but increased significantly thereafter. A statistically significant diurnal variation in corneal backscatter was seen. The diurnal variation in IOP was negatively correlated to the change in corneal backscatter, possibly due to the repeated exposure of the epithelial cells to the preservatives found in the anaesthetic drops used (Hillenaar et al. 2011a).

As age increases, more light is scattered from the cornea (Kline 1991; Mainster and Turner 2012). Olsen (1982) used back scattering techniques to find an increase in light scatter with age; this was thought to be due to increasing irregularity of the spacing of the collagen fibrils. Laing et al. (1979) looked at the endothelial mosaic using a specular microscope and found that the cells in the unicellular layer were equal in size and normally distributed around an average of 20μm, increasing to 30μm in someone at the age of 70. This increase is likely due to increased cell hydration with age or due to cell loss (Carlson et al. 1988; Doughty and Dilts 1994). In addition, the regular hexagonal shape of the cells in the young are replaced by more irregularity as we get older (Malik et al. 1992). This greater irregularity may also be a reason for greater intraocular scatter (Weale 1982). As we get older the corneal endothelium (which is largely responsible for regulating water content in the stroma) changes. We are born with a set number of endothelial cells; these do not regenerate and therefore decrease in number as we get older. This reduces the ability of the cornea to maintain its proper hydration leading to corneal oedema (figure 2.1) and a loss of corneal transparency (Gipson 2013).

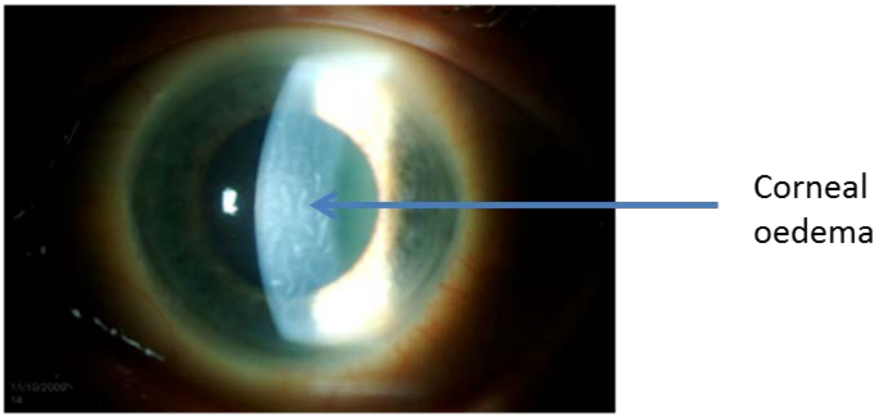



Figure 3.1 showing corneal oedema. This can affect the transparency of the cornea. As the number of cells found in the corneal endothelium decrease with age, the cornea loses its ability to maintain proper hydration. As a result oedema can occur, altering the structure of the corneal stroma and producing a greater amount of light scatter.

### 3.3 Refractive surgery

DG experienced under mesopic or scotopic conditions is a problem many people face even in those who otherwise have satisfactory vision during the day. The number of night vision complaints has increased as the number of people who have undergone refractive surgery procedures have increased (Fan-Paul et al. 2002). As the cornea plays such an important role in the total refracting capability of the eye and is readily accessible, most refractive surgery procedures have focussed on this structure. Myopia can be treated by reducing the steepness of the central cornea and therefore reducing the power of the cornea. Hyperopia is produced by increasing the steepness (Fan-Paul et al. 2002).

There are four main types of refractive surgery that have been used over the years in an attempt to control refractive error. Radial keratotomy (RK) involves making incisions into the cornea in an attempt to reduce myopia. With this technique amounts of light scatter are found to increase as the pupil size increases and more of the incisions placed are exposed by the pupil margin (Veraart et al. 1992; Fan-Paul et al. 2002).

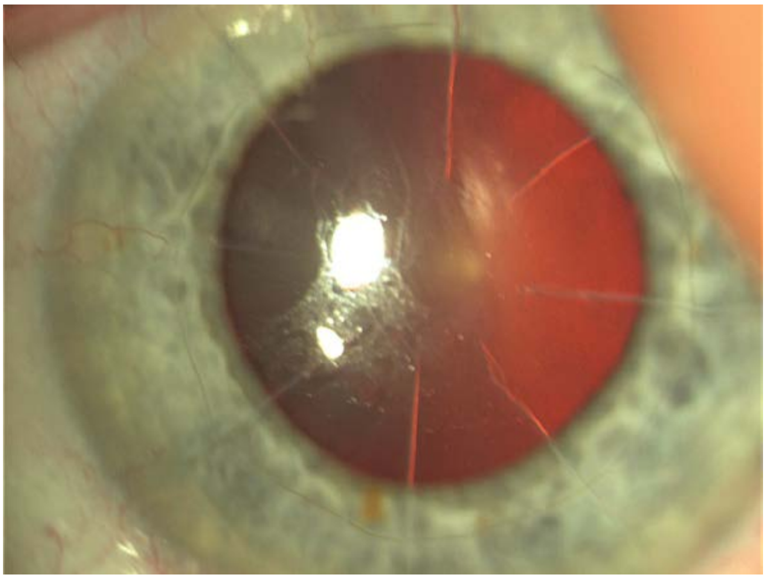


Figure 3.2 showing the incisions made after radial keratotomy (RK) surgery. This is one tyre of surgery used to change the refractive power of the cornea and hopefully negate the need for spectacle correction. Image courtesy of the Gulani Vision institute.

Photorefractive keratectomy (PRK), laser assisted sub-epithelial keratectomy (LASEK) and laser assisted in-situ keratomileusis (LASIK) are all excimer laser based techniques that ablate areas of the corneal stroma in order to change its refracting power. Studies involving PRK have shown no significant increase in intraocular scatter compared to the rest of the population (Harrison et al. 1995; Schallhorn et al. 1996). More recent studies involving both PRK and LASIK have shown similar findings (Lorente-Velazquez et al. 2010; van Bree et al. 2011b). Somewhat surprisingly it has even been found that following LASIK/LASEK surgery, levels of intraocular light scatter were reduced compared to pre-operative values (Nieto-Bona et al. 2010; Rozema et al. 2010a). Increased pre-operative straylight levels have been shown to correlate well with stronger myopic prescriptions (Rozema et al. 2010b). Lapid-Gortzak et al. (2010) also found elevated intraocular light scatter values in preoperative compared to postoperative myopes. This finding was attributed to ill-tolerated contact lenses and was more pronounced in higher myopes and therefore it may be more accurate to report that high myopes may experience reduced levels of light scatter after refractive surgery. Complications to LASIK surgery such as epithelial ingrowth that occurs in 1-20% of all postoperative cases can cause an increase in light scatter (Lapid-Gortzak et al. 2009).

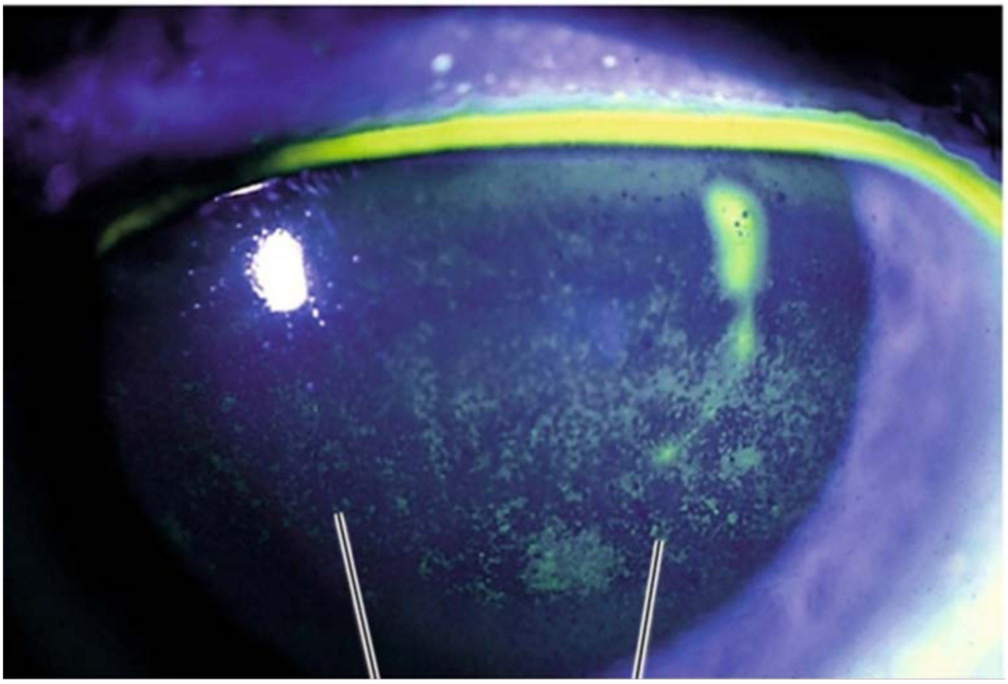
### 3.4 Contact lenses

In early studies involving contact lens wearers, amounts of light scatter from the cornea were found to be significantly higher than those in age matched non-wearers. Those wearing RGP lenses were also found to have a greater amount of scatter from the cornea than those wearing hydrophilic lenses (Elliott et al. 1991d; Mitchell and Elliott 1991), however this situation was reversed on removing the lenses with RGP wearers showing less corneal light scatter. After removal of hydrophilic contact lenses the amount of light scatter from the cornea was found to decrease linearly over time in a similar fashion to the decrease in corneal swelling (Fonn et al. 1999). This increase in light scatter in contact lens wearers is caused by corneal oedema arising from contact lens induced corneal hypoxia with corresponding hypercapnia ($CO_2$ accumulation) (Mandell et al. 1970; Liesegang 2002). To avoid corneal oedema, hypoxia should therefore be minimised (Rho et al. 2014). In soft contact lens wear there are two main ways that hypoxia can be reduced. Firstly the oxygen transmissibility of the lens can be increased although this is somewhat limited by the material and structure of the lens itself, and secondly by enhancing the tear exchange rate between the posterior lens and the cornea (Polse 1979; McNamara et al. 1999; Chauhan and Radke 2001).

Increased corneal light scatter has been shown in some hydrogel lens wearers (Applegate and Wolf 1987) although not all (Applegate and Jones 1989) and greater intraocular light scatter has been shown in contact lens wearers when compared to spectacle wearers (Nio et al. 2003). As contact lens design has improved, normal values of corneal light scatter have been observed in soft contact lens wearers although elevated levels were still seen in RGP lens wearers (van der Meulen et al. 2010). This difference was attributed to subclinical effects of RGP contact lens wear on the cornea.

### 3.5 The tear film

Dry eye disease is a common disorder of the tear film and ocular surface. In early stages patients may be asymptomatic but in later stages chronic discomfort, blurred or fluctuating vision and photophobia can lead to impaired visual function, impacting on quality of life and health status (Goto et al. 2002; Huang et al. 2002). Dry eye disease has been shown to affect between 5 and 30% of people depending on the classification used (Report of the Epidemiology Subcommittee of the International Dry Eye WorkShop 2007). CS measures have been shown to be reduced in dry eyes when compared to normal eyes (Rolando et al. 1998). In people with severe aqueous deficiency and irregular corneal surfaces, artificial tears were found to relieve irritation and improve visual function (Liu and Pflugfelder 1999).



Punctate keratopathy

Figure 3.3 showing an eye with punctate epithelial keratopathy. Dry eye can lead to such changes to the cornea reducing aspects of visual function.

Huang et al. (2002) investigated CS using the FACT chart and DG using the Terry vision analyser (InnoMed, Brea, California, USA) in three participant groups. Group 1 included people with dry eye and punctate epithelial keratopathy, group 2 including those with dry eye without keratopathy and group 3 were normal, without dry eye. Half of participants from group 1 were unable to complete the DG test and CS was found to increase significantly after instillation of artificial tear drops. For group 2 and 3 CS was found to be unchanged after instillation of artificial tears. The only significant improvement in groups 2 and 3 with artificial tears was the significant reduction in the amount of DG experienced at low spatial frequencies. This study concluded that tear film changes in dry eye patients may lead to DG, however in early stages these changes are probably too subtle to be detected by CS measures. This finding is likely dependent to some extent on the test used. The FACT chart has been shown to suffer from ceiling and/or floor effects which may mask subtle differences between some participant groups (Pesudovs et al. 2004).

Puell et al. (2006) also investigated those with dry eye and their visual performance under the influence of glare. DG was found to be higher in dry eye patient's at all spatial frequencies when compared to age-matched norms. The differences found here are likely explained by excluded participants and the glare test used by Huang et al. Those most affected by dry eye were excluded from the comparison as they were unable to complete the glare test and the Terry vision analyser uses an unreliable external torch as its glare source (Puell et al. 2006).

### 3.6 Iris colour

Iris colour is normally determined by melanocytes forming the double-layer posterior pigment epithelium at the back of the iris as well as the content of melanin in the anterior border layer of the iris stroma (Nischler et al. 2013). The number of melanocytes present does not seem to affect iris colour, more the melanin pigment quantity, packing and quality (Wielgus and Sarna 2005).

Iris colour fully develops during infancy and does not alter significantly in later life. Some epidemiology studies suggest that the iris becomes lighter in old age, which may be a result of a change in the melanosome granule morphology, similar to changes in the retinal pigment epithelium cells with ageing (Hu et al. 1995).

The main function of the iris is to control the amount of light entering the eye through the pupil, controlling retinal illumination and image quality. Pupil size decreases with age and has been found to be independent of gender, refractive error or iris colour (Winn et al. 1994; Bergamin et al. 1998). However as well as light entering the pupil, some light also manages to pass through the iris itself, lighter irises transmitting more light to the retina than darker irises. This light entering through the iris does not partake in image formation but instead gives a veiling effect of light over the retina interfering with image clarity (van den Berg et al. 1991).

### 3.7 The Crystalline lens

The crystalline lens is situated directly posteriorly to the iris, anteriorly to the vitreous and is one of the main refractive components of the eye. The strongest refractive component is the cornea directly followed by the lens but the lens has one main difference. It is the part of the eye that when young, enables ocular accommodation. This is provided by ciliary muscle contraction allowing the lens to take up a more curved shape (Coleman 1970). During the life of the crystalline lens it is subject to many physiological changes. From an early age the lens begins to change. There is a gradual loss of transparency leading to a greater amount of light scatter and a steady reduction in the amount of accommodation that can be achieved.

The lens itself is composed of ectodermal cells surrounded by the lens capsule which is made up of a basal lamina (Michael and Bron 2011). The fibre cells at the surface have a nucleus and are therefore metabolically active. The deeper lying fibre cells which make up most of the adult lens are organelle free (Kuwabara 1975; Bassnett and Beebe 1992).

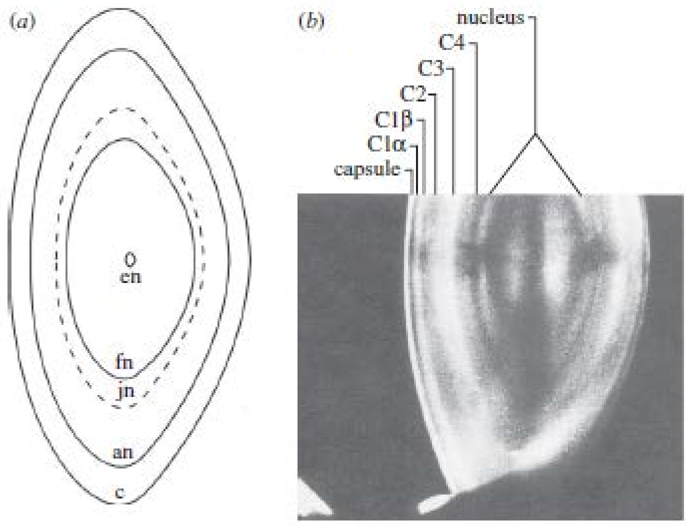



Figure 3.4 a) Diagram of lens zones: (en) embryonic nucleus, (fn) Foetal nucleus, (jn) juvenile nucleus to end of second decade, (an) adult nucleus b) Scheimpflug image of a normal adult lens showing how the different cortical zones form with age (Michael and Bron, 2011).

While the embryonic lens is supplied with blood, the late foetal, juvenile and adult lenses are completely free of a blood supply making sure that light is not absorbed by haem pigments (Bassnett et al. 2011). The water and ionic environment of the lens is maintained by ion pumps (Mathias et al. 2010).

The transparency of the lens is achieved due to a number of factors. At the cellular level there is limited scattering by cellular organelles as there are few found in the central epithelium (Michael and Bron 2011). Recent research indicates that transparency of the lens fibre cells is brought about by the soluble crystallin aggregates being present as densely packed spheres, reducing fluctuations of protein density and refractive index meaning that scattering is low (Michael and Bron 2011). In the lens cortex, high transparency is obtained due to the high spatial order of the fibres and narrow intercellular spaces (Michael and Bron 2011). In the lens nucleus the high spatial order of the crystallins is less important. This is due to the similarity in refractive index between the fibre membranes and the cytoplasm, reducing the amount of light scatter (Michael et al. 2003; Costello et al. 2008). The concentration of cytoplasmic proteins is higher in the cells near the centre of the lens than in those closer to the surface. This means the refractive index of the central lens is slightly higher than in the periphery. The gradient in refractive error this produces helps to correct for longitudinal spherical aberrations (Bassnett et al. 2011). The refractive index of the young lens varies from 1.380 near the surface to 1.409 near the centre (Kasthurirangan et al. 2008).

During its life, the lens undergoes many biophysical and biochemical changes. These changes lead to increased light scatter, colouration and stiffness and tend to affect the lens nucleus to a greater extent than the cortex (Michael and Bron 2011).

All living cells are constantly under oxidative attack (Michael and Bron 2011). In the lens, homeostasis is achieved by having additional scavenger molecules and repair systems located in the cell membranes. These systems achieve a stable environment (Lou 2003; Michael and Bron 2011). Reduced glutathione (GSH), is the most important molecule for regulating the amounts of Oxygen found in the lens (Giblin 2000). The synthesis and recycling of GSH falls with age (Rathbun 1986). A low ratio of GSH in the adult lens makes the nucleus much more susceptible to oxidative attack (Michael and Bron 2011). There is an almost linear reduction in GSH with age (Harding 1970) and with it the ability to protect lens protein structure from the risk of oxidation. Low or even immeasurable quantities of GSH are present in the lens nucleus in nuclear cataract patients (Michael and Bron 2011). Sweeney and Truscott (1998) demonstrated the appearance of a barrier to the inward diffusion of GSH to the lens nucleus after the age of 30 years going someway to explain this predisposition to oxidative attack.

Oxidative attack on the lens results in increased light scatter, reduced transparency and increased hardening of the nucleus, gradually leading to nuclear cataract formation (Michael and Bron 2011).

The susceptibility of the older human lens to oxygen was highlighted in a study involving patients undergoing long term hyper-baric oxygen therapy (Palmquist et al. 1984). In this study 15 of the subjects tested had clear lenses at the start of treatment. Fourteen of these developed an increase in myopia (myopic shift), seven developed obvious nuclear cataract and seven showed an increase in nuclear opacification during treatment. The subject with no increase in either myopia or nuclear opacification was 23 years old; every other subject in this study was above the age of 40. In the un-treated control group no sign of increased myopia or increased nuclear opacification was observed. This shows the obvious problems the ageing lens has in dealing with increased oxygen levels (Beebe et al. 2011).

The vitreous gel also plays a part in the amount of oxygen reaching the lens. The gel like structure of the vitreous body ensures that the only way molecules can travel throughout its structure is by diffusion (Barton et al. 2007). Much of the oxygen that is found in the vitreous is used by the retina, producing an oxygen gradient close to its surface (figure 3.5a) (Alder and Cringle 1990). Other studies have shown that in both human and rabbit eyes, oxygen concentrations are low in the central vitreous and near the lens (Barbazetto et al. 2004; Holekamp et al. 2005; Shui et al. 2006).

When most retinal surgeries are performed the vitreous gel is generally replaced by a saline solution, permanently altering its physical state (Beebe et al. 2011). This saline solution allows for greater agitation of the molecules present in the vitreous chamber, distributing oxygen away from the retina and throughout the chamber (figure 3.5b) (Stocchino et al. 2009). The degeneration of the vitreous body, normally with ageing, has also been found to be associated with increased nuclear opacification (Rosen 1962; Harocopos et al. 2004). This means that vitrectomy or any degeneration of the vitreous gel would likely increase the amount of oxygen delivered to the lens and therefore the likelihood of nuclear cataract formation (Beebe et al. 2011).

Normally the vitreous also consumes a small amount of the oxygen present within it. This oxygen is removed by a compound called ascorbate that is present in the vitreous gel (Beebe et al. 2011). As the vitreous gel degenerates or is completely removed in vitrectomy, the reduced levels of ascorbate in the vitreous chamber would also make the lens more susceptible to oxidative attack (Beebe et al. 2011).

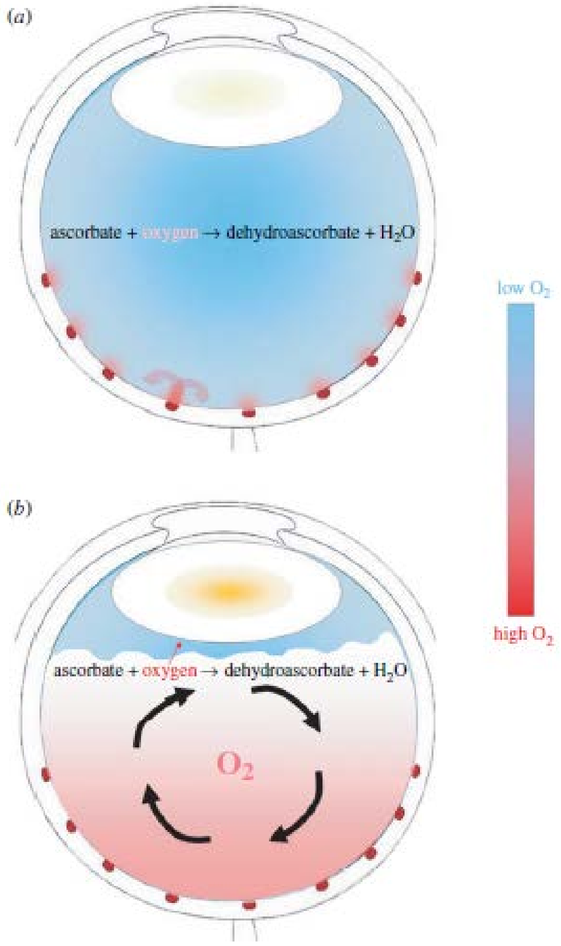



Figure 3.5 a) a normal eye where there is an oxygen gradient close to the fundus. The vitreous has a gel like structure restricting the movement of oxygen. Ascorbate helps to removes oxygen from the vitreous. b) After degeneration or removal of the vitreous body there is little ascorbate left to aid in oxygen removal and the replacement saline solution allows oxygen to move freely throughout this space. A greater proportion of oxygen is able to reach the lens, increasing the likelihood of nuclear cataract formation (Beebe et al, 2011).

### 3.8 Cataract

Hess and Woo (1978) first described the effects cataract can have on the CSF. They discussed that CS measures at different spatial frequencies gave a more complete idea of visual function than solely using VA. CS also correlates better with a patient's perceived visual complaints (Elliott et al. 1990a). DG can also have a drastic effect on CS measures, particularly in patients with cataract (Elliott and Bullimore 1993; van Rijn et al. 2005; Babizhayev et al. 2009).

Despite this CS (and most likely DG, as in many cases the same charts are used for both) is not measured as part of a routine eye test in the UK, most likely due to lack of practitioner understanding and time constraints (Latham 1998).

Intraocular light scatter (otherwise known as straylight), which leads to DG has been investigated previously (Paulsson and Sjostrand 1980; Elliott and Bullimore 1993; van Rijn et al. 2005; van den Berg et al. 2009b). Patients with nuclear, cortical and posterior subcapsular cataracts have all been found to suffer from more intraocular light scatter than aged matched norms (de Waard et al. 1992). When cataract severity in the subpopulations was equated on the basis of VA it was found that the people with subcapsular opacities generally suffered from the most straylight but individual results varied considerably (van den Berg et al. 2013).

Each type of cataract affects vision in slightly different ways. These include increasing myopia and astigmatism, monocular diplopia, reduced light transmission and changes in colour perception (Brown 1993). Each of the three main types of cataract described below are shown in figure 3.6.

Cortical cataracts are cuneiform or wedge shaped opacities in the lens cortex. Light scatter is generated from these opacities as light passes through irregular regions of different refractive index (Elliott 1998). Cortical opacities generally originate in the lens periphery meaning early changes to the lens are shielded by the pupil. Vision is only affected if the cortical spokes enter the pupillary area.

Nuclear cataracts present as a generalized hazing of the lens leading to uniform increase in light scatter from the nucleus (Elliott 1998). They are normally associated with increased yellowing or brunescence of the lens although this can sometimes occur to some degree in normal ageing.

Posterior subcapsular cataracts (PSC) are opacities which form in the posterior lens. They can cause a dramatic reduction in vision due to their central pupillary position especially in situations involving pupillary miosis.

Klein et al. (1992) were able to show that cataract causing a VA of worse than 6/9 had a prevalence of 5% in the 55-64 age group, increasing to 40% in the over 75s. This was based on results generated from 4926 US citizens. More recently, The Blue Mountain study, a large epidemiology study based in Australia investigated the prevalence rates of the different forms of cataract. Mitchell et al. (1997), using data from 2501 people aged between 49 and 96, found that Nuclear cataract was the most prevalent morphological type (51%), followed secondly by cortical opacities (23%) and then PSC opacities (6%).

Grading scales are used both to quantify and to differentiate the cataract present. Numerous schemes exist for classification of cataract, differentiating between the three main morphological types of cataract seen in the ageing eye. Most are designed for slit-lamp based observations, where grading is done in comparison with standard diagrams or photographs (Mitchell et al. 1997). One of the most common of these is the Lens Opacities Classification System III (LOCS III) developed by Chylack et al. (1993b) (figure 3.6). This has evolved over several iterations and grades cataracts over four dimensions: nuclear colour (NC), nuclear opalescence (NO), cortical opacity (C) and PSC opacity

(P). Nuclear, cortical and PSC changes are measured using a decimal scoring system allowing the user to interpolate in 0.1 unit steps between the photographic reference images. Nuclear changes are given a score between zero and seven, cortical and PSC changes between zero and six. These smaller step sizes than other cataract grading systems allow for greater discriminative ability (Chylack et al. 1993b).

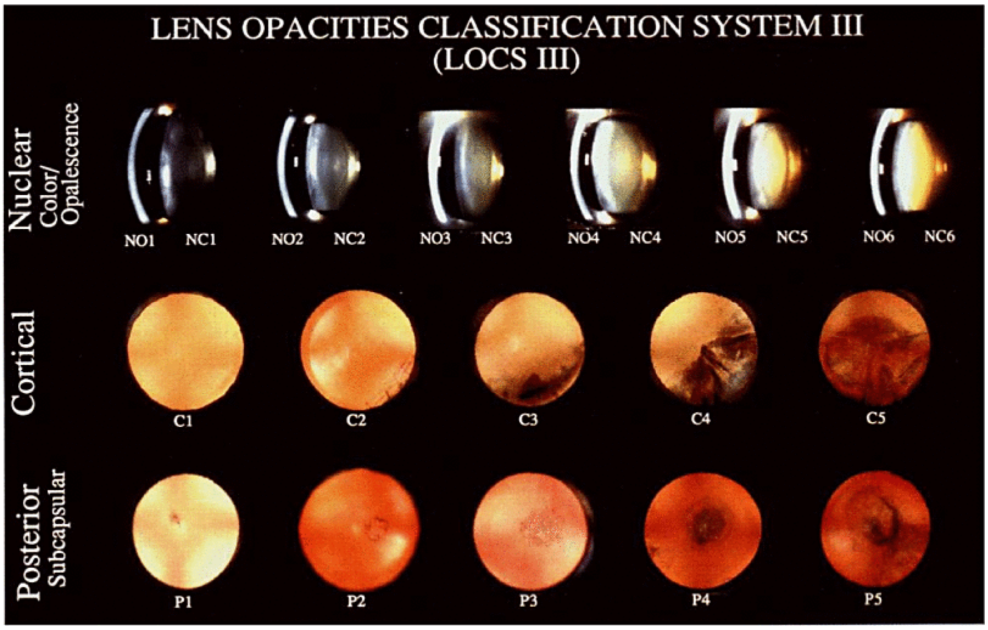



Figure 3.6 LOCS III grading system showing the different levels of each type of cataract (Chylack et al. 1993b).

### 3.9 Pseudophakia

In the developed world, when a cataract reaches a point where it is affecting vision to a significant extent, the lens is replaced by an artificial intraocular lens (IOL). This however brings a new set of problems. Do different materials/types of IOL produce a higher proportion of light scatter than others and is light scatter increased by a common side effect of cataract surgery, posterior capsular opacification (PCO)?

Miller and Lazenby (1977), using a glare tester measuring CS with and without glare, found that the process involved in leaving a patient aphakic did not affect DG. Secondly, DG was not significantly affected in aphakes when compared to normal participants.

Weatherill and Yap (1986) investigated different IOL lens designs to see if there was any difference in CS attenuation among 73 patients with anterior chamber, posterior chamber and iris supported IOL's. They used a TV monitor to present sinusoidal gratings at six different spatial frequencies. A criterion-dependent psychophysical method was used i.e. the observer was asked to respond when the grating was just visible. This study concluded that contrast loss in all pseudophakic patients was similar and likely to be independent of lens design.

A number of studies have found that CS in the eyes of otherwise healthy patients, who had undergone successful posterior chamber IOL implantation, was no different to that of aged matched norms (Owsley et al. 1985; Weatherill and Yap 1986; Furuskog and Nilsson 1988). Others have shown that DG is higher in those with posterior chamber IOLs than aged matched norms (LeClaire et al. 1982; Nadler et al. 1984; Van Der Heijde et al. 1985). The presence of PCO in these studies, something shown to increase the amount of light scatter was not accounted for (Knighton et al. 1985). More recently (Nischler et al. 2010) in a study involving the driving population found that CS and intraocular light scatter was no different between pseudophakes and aged matched norms. Again people with PCO were not removed from this study and so the different findings to earlier studies by (LeClaire et al. 1982; Nadler et al. 1984; Van Der Heijde et al. 1985) may relate to improvements in cataract operations, improvements to IOL design and quality over time or that superior CS and glare measures were used.

Successful cataract operations have been shown to substantially improve visual performance compared to the cataractous lens (Masket 1989). When assessing cataract and pseudophakic patients and the differences in visual function between these groups, measures of CS and DG have been found to be independent of VA measures (Rubin et al. 1993).

Superstein et al. (1999) tried to quantify cataract patients' visual complaints in an attempt to correlate these with objective DG and spatial CS findings. They examined 30 cataract patients with VA of 6/21 or better with no other ocular pathology. Visual function was examined preoperatively and within three months postoperatively. Also measures of CS and VA in the presence of glare were made and an idea of a patient's perceived visual performance was also generated by the use of the Activities of Daily Vision Scale (ADVS) questionnaire. Preoperatively patients had reduced VA and CS in the presence of glare and the ADVS scores were correlated with visual performance. Postoperatively a significant improvement in VA and CS in the presence of glare as well as in the subjective report of visual performance reported by ADVS was found. It was concluded that all these factors should be considered in the evaluation of cataract patients.

As technology moves on and more material options become available for IOL use, interest has shifted to lens material and design. Differences in VA, CS and colour vision performance from both acrylic and silicone IOL's has been shown to be negligible up to three years postoperatively (Miyata et al. 2009). This finding for CS should perhaps be viewed with caution as the testing method used (FACT discussed in chapter 5) has been found to be inappropriate for cataract surgery outcomes research (Pesudovs et al. 2004).

The use of multifocal IOLs has also come to the fore. The literature initially appears to be mixed in its idea as to whether or not multifocal IOLs degrade visual function over and above the effect of monofocal IOLs. A couple of studies have measured poorer CS with the use of multifocal IOLs using the FACT system (Montés-Micó and Alió 2003) and Pelli-Robson measures (Rocha et al. 2005). This reduction in visual function is supported by theoretical predictions of IOL performance (Holladay et al. 1990). Dick et al. (1999) however, found no difference between CS results in those with multifocal or monofocal IOLs. This study used a variation on the straylight meter (described in chapter five) to take DG measures. The differences reported from these studies can be explained. Montés-Micó and Alió (2003) and Rocha et al. (2005) tested patients much sooner post-operatively than the Dick et al. study. Montés-Micó and Alió reported reduced CS levels in their multifocal group during the first three months post-operatively, whereas after six months and beyond no differences between groups were observed. Rocha et al. only tested their participants up to two months after their operations and therefore found reduced visual performane in the multifocal IOL group. Dick et al. however only started testing their participants 4-6 months after their operations. Therefore it appears that initial CS is reduced with the use of mutifocal IOLs, then after six months and beyond performance all participants is similar.

Cerviño et al. (2008) found no difference in intraocular light scatter between multifocal or monofocal IOLs, again using the straylight meter. In this last study testing was done under photopic conditions and therefore changes due to IOL design may well have been limited by natural pupillary constriction.

### 3.10 Posterior capsular opacification (PCO)

The issue of intraocular light scatter affecting visual performance does not begin and end with IOL design and material. Further complications of IOL insertion including PCO may occur, which can affect vision. PCO is the most common postoperative complication of cataract surgery (Apple et al. 1992). PCO causes visual impairment similar to that caused by cataract formation (Knighton et al. 1985; van Bree et al. 2012). It results from a wound healing response where lens epithelial cells are released as a result of the cataract surgery (Wormstone et al. 2009). The cells that are released collect between the IOL and the posterior lens capsule causing opacification known as PCO (van Bree et al. 2012). PCO changes can reduce VA and increase intraocular light scatter (van Bree et al. 2008; van Bree et al. 2011a). The parameter of visual function that is affected by PCO is probably dependent on the size of irregularity. PCO changes that are much larger than the wavelength of light refract light and smaller sized particles scatter light (van Bree et al. 2012). Particles that refract light may predominantly affect vision very close to fixation and reduce VA whereas; smaller particles may have more of an effect over larger angles (visual angles beyond 1°) and increase intraocular light scatter (van den Berg et al. 2009a; van Bree et al. 2011a). The amount of PCO in postoperative eyes has been shown to be more extensive with PMMA lenses when compared to silicone or soft acrylic designs (Hayashi et al. 1998).

Foldable hydrophobic acrylic lenses are used most frequently in cataract surgeries (Leaming 2004). They are however prone to small water inclusions called ‘glistenings’ which can effect visual performance (Bellucci 2013). Hydrophilic acrylic designs are also used frequently in Europe (Bellucci 2013). However, they have been shown to be more prone to the formation of PCO than hydrophobic designs (Findl and Leydolt 2007). Silicone lenses, despite their good PCO blocking effects (Findl et al. 2005) are used less frequently as they are less suitable for micro-incisions (Bellucci 2013).

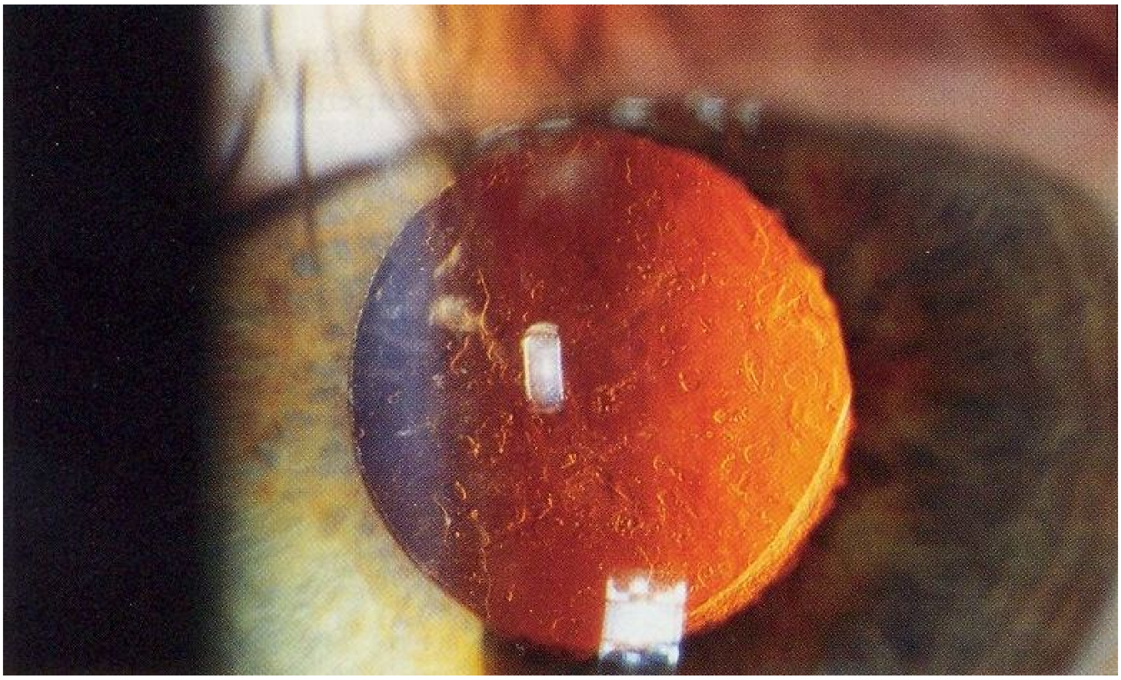


Figure 3.7 showing the appearance of typical PCO changes (image courtesy of Rakesh Ahuja, MD)

## 3.11 Vitreous

A previously eluded to in section 3.7 the vitreous gel fills the space between the lens and the fundus and plays an important role in reducing oxygen transmission to the posterior lens. In the young healthy eye a compound called hyaluronan separates the collagen fibres in the vitreous gel, allowing light transmission with little to no scatter (Sebag 2014). Even in the normal ageing eye negligible changes have been recorded in the transmissibility of the vitreous gel (Wolf and Gardiner 1965). Therefore where no vitreopathy is evident studying the lens alone can effectively describe how these two structures effect visual performance when a glare source is present (Wolf and Gardiner 1965).

Over time the hyaluronan dissociates from the collagen fibres leading to the formation of collagen aggregates (floaters) which occur throughout the vitreous body (Los et al. 2003). Floaters are most commonly reported after posterior vitreous detachment (PVD) and in myopic vitreopathy (Murakami et al. 1983). Marfan syndrome, Ehlers-Danlos syndrome and diabetic vitreopathy are also known to be associated with the aggregation of collagen fibres resulting in glare due to light scatter (Sebag 1989; Sebag and Yee 1998). A small sample study was able to show a significant increase in intraocular light scatter in eyes that are affected by floaters (Castilla-Marti et al. 2015).

Vitrectomy or removing the vitreous gel offers a definitive solution to floaters. However vitrectomy is also associated with cataract formation, retinal detachments, vitreoretinal haemorrhages, endophthalmitis and macular oedema (Wilkinson 2011). Due to the risks involved it is normally restricted to those where floaters cause significant visual disturbance (Sebag 2014).

### 3.12 Fundus

The fundus is the third main source of light scatter, contributing to the veil of light produced by a glare source in the young, healthy eye. The scattering, or a better term may be reflectance, of light from the fundus is strongly influenced by melanin concentration in the choroid and retinal pigment epithelium (RPE) and by the macular pigment at the fovea (Delori and Pflibsen 1989). The concentration of melanin appears to be the most important factor in fundus reflectance. As the amount of melanin pigment observed in the eye increases, a greater proportion of light is absorbed resulting in less reflectance (Delori and Pflibsen 1989; Ginis et al. 2013). Melanin concentration reduces with age due to a loss of melanin granules and the accumulation of lipofuscin granules in the RPE (Boulton and Dayhaw-Barker 2001).

Visual discomfort, DG and photostress recovery time have all been shown to improve significantly with greater amounts of macular pigment (Stringham et al. 2011). Macular pigment concentrations were also found to be higher in those with darker irises (Stringham et al. 2011). It is not altogether clear how macular pigment concentrations change with age in the absence of ocular pathology or dietary deficiencies (Whitehead et al. 2006). In one study macular pigment was shown to decline with increasing age (Elsner et al. 1998). A more consistent finding is shown in those with age related macular degeneration (AMD), where macular pigment density decreases (Beatty et al. 2001; Bone et al. 2001).

There is a wavelength dependency to reflectance from the deeper layers of the fundus like the choroid. Red light penetrates the fundus further than green light and produces a diffuse back scatter from the choroid (Delori and Pflibsen 1989; van den Berg 2010). The red light produces a greater amount of reflectance from the fundus than does shorter wavelength light especially at smaller angles (Ginis et al. 2013). At larger angles this wavelength dependency disappears.

### 3.13 Light Scatter

The amount of light scatter observed inside the eye is of considerable interest for two main reasons. Firstly it leads to an impairment of retinal image formation by producing a veiling luminance over the retina (forward light scatter). Secondly using slit lamp biomicroscopy, it can act as a measure of corneal or lenticular pathology (backward light scatter), the most prevalent being cataract (Weale 1986). Forward and backward light scatter are not always predictive of one another and on occasion a large amount of back scatter from a lens is poor at predicting visual performance (Sigelman et al. 1974). Weale (1986) used a polarising filter and analyser with their two axes crossed, to try to establish whether the light seen with a slit lamp was actually backscattered or reflected by the lens. If all the light was reflected the lens would appear dark as the reflected light would not be seen through the polarising filters. In a normal 70 year old lens around half the light was shown to be backscattered and half reflected. This would indicate that the amount of “back scattered” light from the lens is a mixture of both reflected and scattered light (Weale 1986).

The consideration of how well backward light scatter, observed when using equipment such as the slit lamp, faithfully reflects the amount of forward light scatter, the functional effect of scatter on visual performance was of great interest (van den Berg et al. 2013). In work using human donor lenses it was shown that forward and backward light scatter were produced by different processes (van den Berg 1997). This may go some way to explain why correlations between measures of forward light scatter and backward light scatter have been shown to be poor in a number of patient studies (Elliott and Hurst 1989; Elliott et al. 1991c; de Waard et al. 1992).

### 3.14 Backward light scatter

Backward light scatter is the light scattered back from the ocular media which can be seen on equipment such as the slit lamp. Techniques like the Interzeag Opacity Lensmeter 701 and Scheimpflug photography, which attempt to quantify levels of back scattered light, have shown poor correlations between levels of back scatter and measures of visual performance in people with certain cataract morphologies (West and Taylor 1986; Elliott and Hurst 1989). In vivo confocal microscopy, used in helping the diagnosis of rare corneal degenerations and dystrophies (Hillenaar et al. 2011a) would also struggle with identifying scatter from different lens areas due to the very high magnifications involved.

The analysis of back scattered light has proved useful in providing information about the transparency and quality of optical tissues. Several procedures have been developed for analysing back scattered light from the cornea and lens by means of digital analysis of images obtained by slit lamp or Scheimpflug camera. Bueno et al. (2007) developed a system for quantifying the amount a back scattered light present by means of a digital analysis of the fourth Purkinje image.

### 3.15 Forward Light scatter

Forward-scattered light produces a veiling luminance over the retina and therefore results in a reduction of retinal contrast. Back-scattered light theoretically only reduces the amount of light reaching the retina (Atchison and Smith 2000); therefore, for the purposes of this project, forward-scatter is the more interesting phenomenon. As mentioned previously, poor correlations between back scatter and forward scatter measures have been shown in certain people. Measurements of forward light scatter would therefore give a better indication of visual performance.

The effect of forward light scattering is perhaps partially allayed due to the directional sensitivity of the photoreceptors, known as the Stiles-Crawford effect (light entering the centre of the pupil is around five times more effective than light entering the periphery of the pupil) (Snyder and Pask 1973; Marcos and Burns 2000). This relates mainly to the cones so is a photopic phenomenon and does not greatly affect the amount of scatter under low light levels (Atchison and Smith 2000).

The forward light scatter in the eye causes DG which gives the perception of a veil of light when a bright light source is presented into the peripheral field of view (van den Berg 1991; Vos 2003a). DG can produce almost a complete blindness close to the light source and hampers visual performance if further away (van den Berg 1995; Vos 1999). Increased visual complaints of glare are in direct relation to age, glare distance and glare angle (Chang et al. 1998; Vos 2003a).

The most widely used current psychophysical method to measure intraocular light scatter is the compensation comparison method. This procedure has led to the basis of the development of a commercially available device called the C-Quant. The patient observes a central stimulus as well as a more peripheral light as a glare source. The central field is divided into two halves which are presented simultaneously to be compared by the observer. The glare source is presented as a flickering light in a peripheral ring of the device. Some of this light is scattered by ocular components of the patient’s eye onto their central retina. A compensation light is presented in one of the two central halves, chosen at random, and flickers at the same frequency but in counter-phase with the peripheral glare source. As the central counter-phased flicker is increased, the perceived flicker seen centrally due to light scatter, is reduced. When the counter-phased flicker matches the perceived flicker due to light scatter, no flickering is seen. The C-Quant uses a two-alternative forced-choice method to determine threshold and the task for the subject is to decide which half of the central circle flickers more strongly (Franssen et al. 2006).

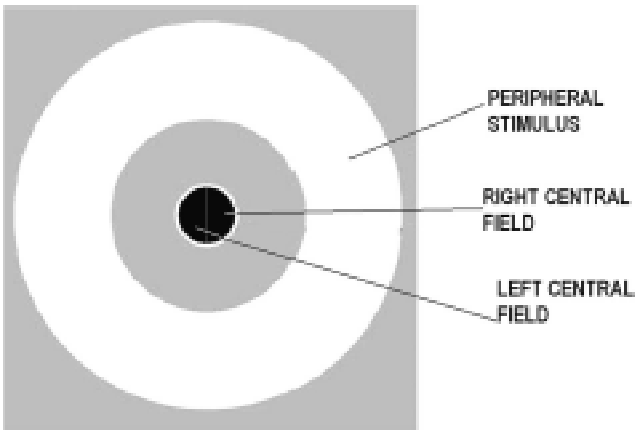



Figure 3.8 showing the stimulus layout for the C-Quant stray light measurement device (Pinero et al., 2010). The peripheral stimulus or glare source is scattered by the ocular media and seen in the central field. A compensation light is added to one half of the central field and the task for the participant is to report which half flickers more strongly.

Previous studies using this method have found the mean value of straylight to be around 0.9 log(s) in healthy young eyes. This value increases from the age of 40 to a mean value of 1.2 log(s) at 70 years and 1.4 log(s) at 80 years of age. With cataract present this can rise to 2.0 log(s) or higher (van den Berg et al. 2009b). This method is the only measure of forward light-scatter which has been validated on different kinds of subjects, using large sample sizes (Pinero et al, 2010).

Straylight can be calculated from the following equation:

$$straylight\ parameter\ s = \theta^2 \times L_{eq}/E_{bl} = \theta^2 \times PSF$$

Where $L_{eq}$ is the equivalent veiling luminance, $E_{bl}$ is the illuminance at the eye from the glare source (in lux) and θ is the angle in degrees of the glare source from the line of sight. The straylight parameter is normally given logarithmically as log(s) (van den Berg et al. 2013).

## 3.16 Optical approaches for measuring image quality and scatter

The point spread function (PSF) is a measure of the image quality of an optical system. The PSF can be thought of as having two main regions; 1) the central, small angle, high intensity domain called the PSF core and 2) the large angle, low intensity domain, normally referred to as intraocular scatter (van den Berg et al. 2009a). Psychophysical techniques for quantifying straylight like the C-Quant assess the larger angle, low intensity domain of the PSF (van den Berg et al. 2009a). Results generated from any psychophysical method depend on patient co-operation and the ability to perform a desired task. Optical procedures provide a more objective measure of image quality (Pinero et al. 2010).

Two main optical approaches have been developed in an attempt to quantify amounts of light scatter. The Double pass (DP) system (figure 3.9) was proposed as a method for estimating retinal image quality almost half a century ago. It records the retinal image after DP through the eyes optics and retinal reflection and has been demonstrated to show an accurate estimate of the image quality of the eye (Artal et al. 1993; Williams et al. 1994). There has been some controversy involving the use of a DP system in order to produce a valid measure of the PSF. A point source of light is projected onto the fundus and the reflected light is recorded. The projected light onto the fundus corresponds to the PSF. A previous study (Martinez-Roda et al. 2011) used an infrared light to produce a DP image and stated that this could be used as a valid measure of the PSF. If the fundus behaves as an efficient reflective surface, the reflected light distribution would have the same shape. However, this was shown not to be the case for red and infrared light (Williams et al. 1994). This is because red light is able to penetrate through the RPE and reach the choroidal layers whereas green and yellow light is not. The reflection from green-yellow light comes from the retina-RPE, useful for more accurate recording of the PSF (van den Berg 2011). Large differences from DP recordings of PSF between green and infrared light are seen (Lopez-Gil and Artal 1997), rendering the approach using infrared light invalid. This suggests that green-yellow light is important for proper assessment of DP images (Lopez-Gil and Artal 1997).

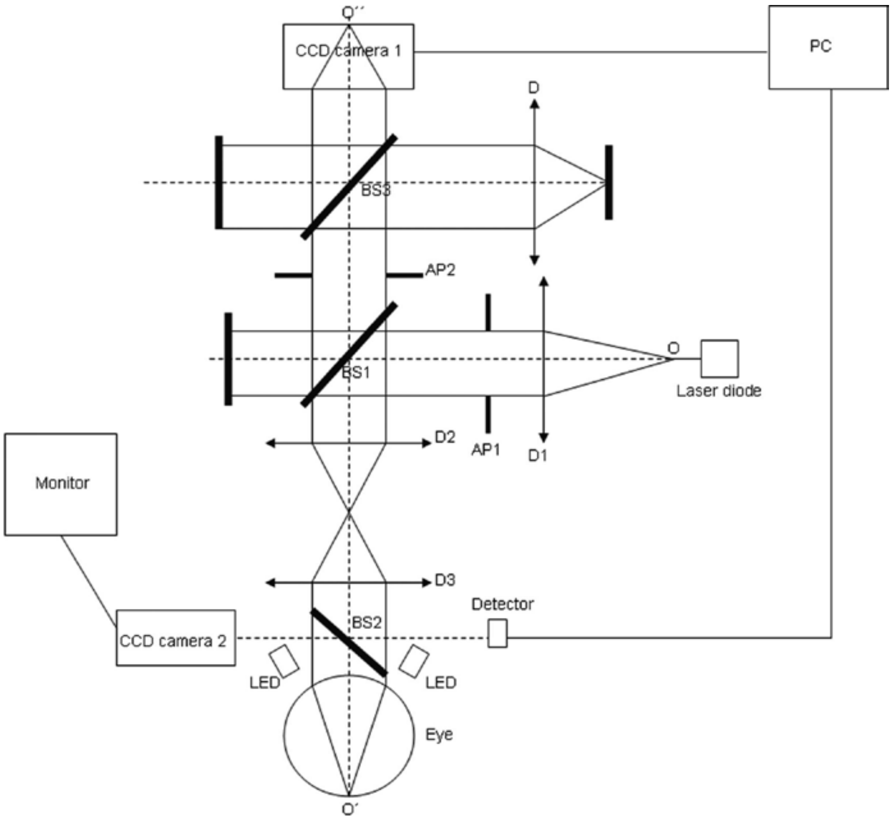



Figure 3.9 showing a schematic of a DP device. The numbers indicate the trajectory of light within the instrument. D is the achromatic double lens; AP the artificial pupil; BS the beam splitter and CCD is charge-coupled device video (Pinero et al. 2010).

The most common wavefront sensor is the Hartmann-Shack sensor (HS) (figure 3.10) and is currently the basis of most methods for measuring ocular aberrations (Liang et al. 1994; Prieto et al. 2000). This system consists of an equi-focal microlens array, conjugated with the pupil of the eye, and a camera placed at the focal length of the micro-lenses. If a distorted wave front reaches the sensor, the pattern of the dots the machine uses becomes irregular. The displacement of each spot from its normal position is proportional to the derivative of the wave front over each microlens area. The information gathered by these sensors is extremely useful but their main drawback is poor precision in cases of significant higher-order aberrations and scattering. This is because of limitations imposed by the microlens sampling (typically more than 100μm apart), (Pinero et al., 2010).

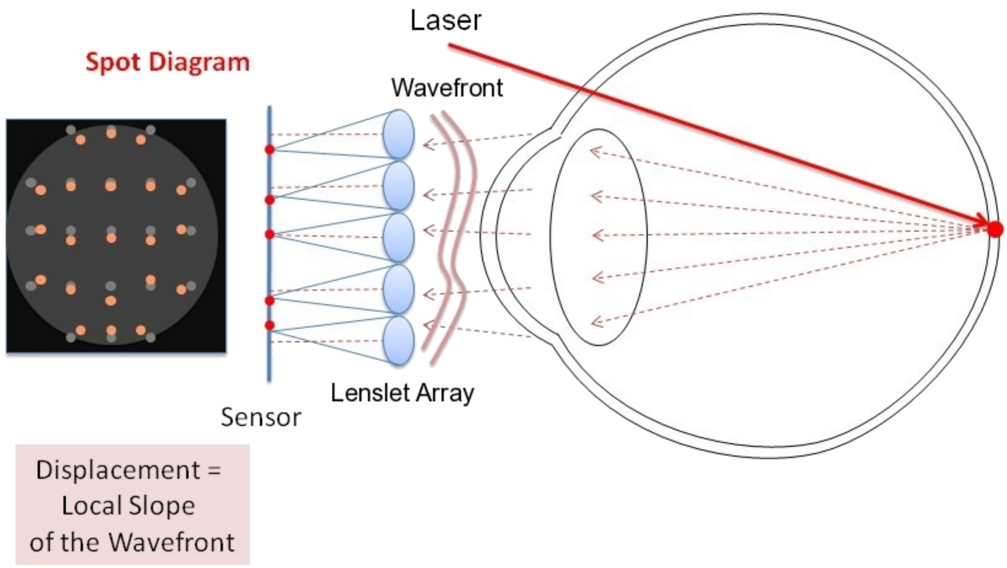



Figure 3.10 Hartmann Shack Aberrometer. (Image courtesy of Vitorpamplona CC-BY-SA-3.0). This gives an idea of the amount of ocular aberrations produced by the eye.

From the images obtained by these systems, the ocular modulation transfer function (MTF) can be calculated. This shows the reduction in contrast due to the optics of the eye on a sine grating as a function of its spatial frequency (Pinero et al. 2010). The MTF generated by the DP is superior to the one generated by the HS system. The DP system includes errors generated from the optical system involved in retinal image degradation and also aberrations of the highest orders, not shown by the MTF generated from the HS system. A system to compare the MTF's from both devices has been described elsewhere (Shahidi and Yang 2004). The difference between the two is often referred to as "scattering" but this is limited to small angles.

In situations where patient responses are unreliable psychophysical methods can become very time consuming and inaccurate (Pinero et al. 2010). The optical procedures provide a more independent measure of light scatter. These are all based on either DP or HS systems or a combination of the two. However, the techniques have the disadvantage that they provide estimations of scatter over a small angle domain where scattering is minimal so limiting their value for many study areas (van den Berg 2017). In a study comparing the straylight meter to the HS system, results showed no significant relationship between the two (Benito Lopez et al. 2015). Additionally some devices based on the DP system provide their estimations of scatter from the analysis of the PSF and assume that the external parts are only down to scatter, not always correct in highly aberrated eyes (Pinero et al. 2010). There are no large sample studies that have been performed with these devices so no normative values are known.

### 3.17 Mie and Rayleigh scatter

When sunlight enters our atmosphere it is scattered by particles in the air. When these atmospheric particles are small, typically less than 1/10$^{th}$ the wavelength of the incident light, scattering can be approximated by the proportion of the 4$^{th}$ power of the wavelength of sunlight otherwise known as Rayleigh scattering (Kerker 1969). This provides an explanation as to why the sky is blue in colour. The blue region of visible light is shorter in wavelength and therefore scattered more than the longer wavelength red light (Gu and Robles-Kelly 2014). In this form of light scatter forward light scatter is equal to backward light scatter. The strength of the scattered field is the same in all directions (Costello et al. 2007; Gu et al. 2015).

The Rayleigh theory of light scattering is for spherical homogeneous particles smaller than the wavelength of incident light (Yguerabide and Yguerabide 1998). When a small particle is exposed to an electromagnetic wave whose wavelength is much larger than the particle diameter, the electrons all sense the same phase of the wave meaning they oscillate and scatter light in the same phase (Yguerabide and Yguerabide 1998).

When light is scattered by particles in the atmosphere that are equal to or larger than the wavelength of incident light, the scattering is better modelled by Mie theory (Kerker 1969). Mie theory states that scattering is proportional to the second power of the wavelength (Gu and Robles-Kelly 2014). Mie theory is generally used to model the scatter caused by haze in the atmosphere. As light scatter is more uniform across wavelengths it causes the characteristic whitewash appearance in haze and cloud (Gu and Robles-Kelly 2014). The Mie theory of light scatter encompasses more general scatter from larger particles and is not strongly wavelength dependant. In this form of light scatter, forward light scatter does not equal backward light scatter, with the majority seen in the forward direction (Gilliland et al. 2004; Costello et al. 2007). Smaller particles contribute to larger angle scatter which is seen in slit lamp images and consistent with the theory of Raleigh scatter (Kerker 1969).

The Mie theory of light scatter is for homogeneous spherical particles of any size (except the very small) (Yguerabide and Yguerabide 1998). When the scattering particle is similar or larger in size than the wavelength of the incident electromagnetic wave, its electrons oscillate at different phases. This leads to interference in the scatter produced by different electrons in different parts of the particle meaning the magnitude and angle of the scatter produced from the particle changes (Yguerabide and Yguerabide 1998).

Spherical particles with diameters of 1 to 4µm have been reported in transparent and cataractous human lenses (Gilliland et al. 2004). These particles are much larger than the wavelength of light and therefore would indicate that light scattering in the eye should use the Mie model of light scatter. In both normal and cataractous eyes most light scatter is not wavelength dependant and thus predominantly of the Mie form (Whitaker et al. 1993). When wearing tinted spectacles the spectral transmission of the tint has been shown to have no benefit in reducing DG (Steen et al. 1993) something that is again predicted by the Mie scattering theory being wavelength independent. Mie scatter predicts that forward scatter is not equal to backward light scatter in the eye, with forward light scatter being most prominent (Costello et al. 2007). Previous studies have confirmed that large amounts of backscatter, mainly observed as smaller particle scattered light (Costello et al. 2007) and reflected light (Weale 1986), is not always representative of the amount of forward light scatter experienced (Weale 1986; de Waard et al. 1992). Correlations between forward and backward light scatter seen with different types of cataract also differ, with nuclear cataract showing most agreement between the two (de Waard et al. 1992). These factors indicate that intraocular light scatter, particularly in the cataractous lens, predominantly follows the Mie theory of light scatter rather than the Rayleigh theory of scattered light. In this respect, light scattering seen in cataract appears white rather than blue.

When a particle is much smaller than the wavelength of light the expression for Mie scatter reduces down to the Rayleigh equation (Yguerabide and Yguerabide 1998).

It is important to remember that the theories of light scatter mentioned above are not two different kinds of scattering, but two methods of calculating how light is scattered by different sized particles (Costello et al. 2007). The physics of light scattering is similar regardless of particle size. The crucial difference for the analysis of light scattering in the lens is that smaller particles scatter a large proportion of light at high angles (30-180°) whereas, with larger particles, this is done at relatively narrow angles. Larger particles also scatter a greater proportion of light relative to their size (Costello et al. 2007).

### 3.18 Illuminance

The amount of DG experienced depends on a number of factors, including:

1) The illuminance caused by the glare source at the eye and 2) The angle of the glare source from the line of sight.

The equation for the equivalent veiling luminance below shows the relationship between illuminance at the eye and the glare source angle ($\theta > 2°$):

$$L_{eqv} = {}^{E}/_{\theta^2} \qquad 3.1$$

Where $L_{eqv}$ is the equivalent veiling luminance, E is the illuminance of the glare source and θ is the angle of the glare source from the eye.

If we consider an encounter with an oncoming car that has its headlights on, neither the illuminance at the eye or the glare angle is going to remain constant as the two cars move towards one another. As the cars approach one another the glare angle increases at a rate that is inversely proportional to the distance. At the same time the illuminance at the eye increases at a rate that is inversely proportional to the square of the distance. The combined effect of these two processes means $E/_{\theta^2}$ remains more or less constant until the car is at a distance where the headlight beam is not seen by the driver (van den Berg et al. 2009b). This means that as the car moves closer the amount of DG experienced is consistent as the effects of distance and angle on $L_{eq}$ virtually cancel themselves out.

The distance of a glare source from a surface has a big impact on the illuminance it produces at that surface due to the inverse square law. This law states that the illuminance a light source produces is inversely proportional to the square of its distance away from the eye.

$$E = \left(I/_{d^2}\right) cos\theta \qquad 3.2$$

Where E is the illuminance at the eye, I is the light intensity, d is the distance in metres and θ is the angle of the light from the line of sight. This shows that on a plane perpendicular to the incident light the illuminance will be completely dependent on distance for a given light source. If the light is moved slightly away from perpendicular, the angle produced can play a substantial part in the illuminance produced at the eye.

This relationship with distance is shown by the figure 3.11 below. If the light is moved from 1m to 2m away from the eye, this 1m change to the distance will reduce the illuminance at the eye by a factor of 4.

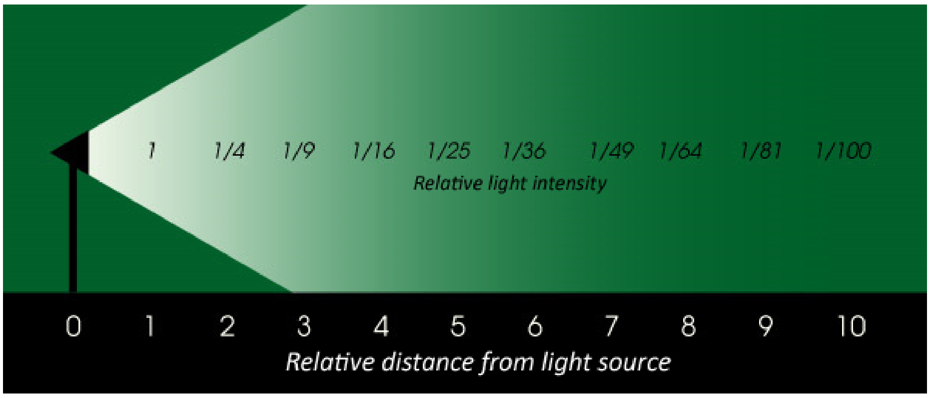



Figure 3.11 Inverse square law.

The angle of the glare source from the eye also has a large impact on the amount of veiling luminance produced by the ocular media.

Equation 3.1 above shows that if the glare angle were to double the amount of veiling luminance experienced would reduce by a factor of four.

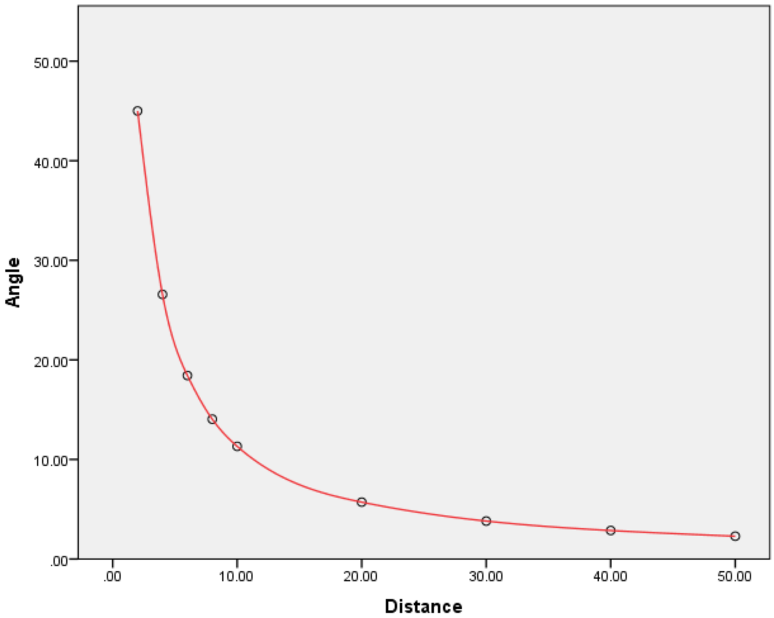



Figure 3.12 showing the relationship between headlight distance and glare angle. When the distance between vehicles is large, the illuminance at the eye is relatively small (inverse square law) and the glare angle is minimal. When the vehicles are very close to one another the illuminance at the eye is relatively large and the glare angle is large. This means the ratio $^{E}/_{\theta^2}$ remains more or less the same at all distances and therefore the amount of veiling luminance remains constant as two vehicles approach each other.

Figure 3.12 allows us to visualise what happens as an oncoming vehicle moves towards us. This was plotted using simple trigonometry assuming that the oncoming vehicle remains at a constant distance (2m to the side) in the oncoming lane.

$$\tan\theta = {}^{opp}/_{adj} \qquad 3.3$$

There is only a slight change in glare angle from distances 20-50m. When the cars get to within 10m of each other and then continue to move closer, the glare angle starts to increase much more rapidly.

In an attempt to confirm that the amount of DG experienced as a car moves closer to us is largely constant figure 3.13 below has been produced. This shows $L_{eq}$ (equivalent veiling luminance in cd/$m^2$) plotted against distance. An estimate of 40,000 candelas was used as the intensity of a car headlight (Aslam et al. 2007) and values of $L_{eq}$ were calculated for distances between 5-100m in 1m steps using the equations 3.3, 3.2 and lastly 3.1. This shows that for any glare distance above 20m $L_{eq}$ is virtually the same to two decimal places. The amount of $L_{eq}$ increases slightly for distances less than 20m. From the data obtained in plotting figure 3.13, the increase in $L_{eq}$ generated between the glare source being at 100m and the glare source being at 5m can be calculated. Over this change in distance $L_{eq}$ increases by a negligible 0.08cd/$m^2$.

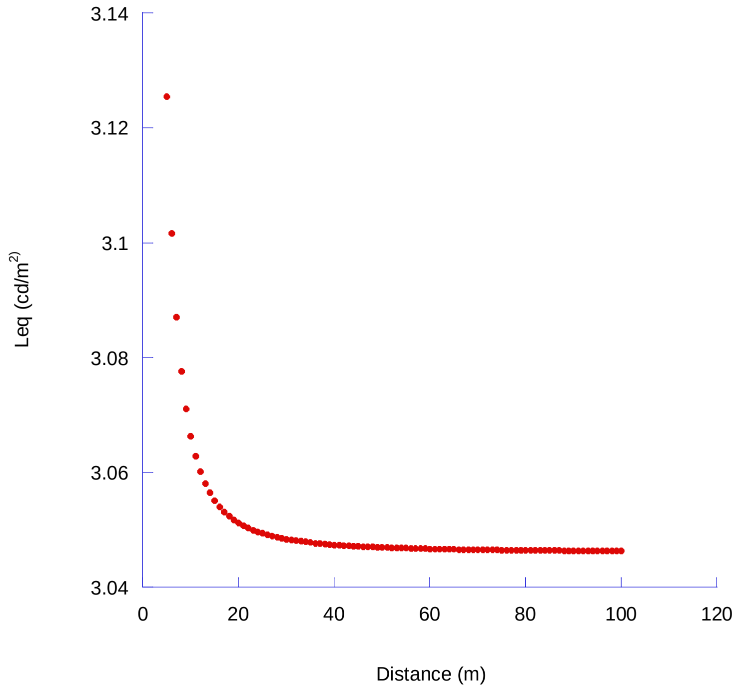



Figure 3.13 showing how $L_{eq}$ varies with distance. Again as an oncoming vehicle approaches there is virtually no change in $L_{eq}$ for distances between 100m and 20m. As the cars get closer still $L_{eq}$ begins to rise. The increase in E as the distance between vehicles decreases (equation 3.2) begins to outweigh the effects of increasing glare angle, therefore leading to an increase in $L_{eq}$.

Figure 3.13 above would indicate that as two vehicles approached each other the veiling luminance experienced by a driver would continue to rise at an exponential rate the closer the cars became. Luckily however, thanks to the edge of the car windscreen there becomes a point where the driver can no longer see the headlights of the oncoming car. Therefore the amount of veiling luminance can be considered as more or less constant as an oncoming car approaches.

### 3.19 Measurements of intraocular light scatter

Intraocular light scatter equates to the amount of light that reaches the retina which does not contribute to the image formation of the stimulus. Normally light rays are refracted by the cornea and intraocular lens, to produce a clear, concise image on the retina. However this process is not perfect and optical imperfections produce scatter of these rays which can lead to a veil of light across the retina. The most common causes of intraocular light scatter are cataracts, corneal dystrophies/oedema and vitreous floaters.

The amount of straylight falling at a given distance from the centre of the retinal image is generally specified as the equivalent veiling luminance, $L_{eq.}$ This indirect method for measuring straylight was called the equivalent veil technique, (Cobb 1911). This measures the proportion of incident light scattered on to the fovea by a glare source at angle θ.

$$L_{eq} = f(\theta) \times$$

Where $L_{eq}$ is the equivalent veiling luminance and $E_{gl}$ (lux) is the illumination on the observer's eye. f(θ) is the proportion of $E_{gl}$ that turns into $L_{eq}$. If the relationship between $L_{eq}$ and $E_{gl}$ is constant for varying illuminance at a given angle, this would show that straylight is the limiting factor on the absolute threshold at that particular point on the retina. For example if you doubled the amount of light reaching the eye, the amount of straylight should also double. If the relationship between $L_{eq}$ and $E_{gl}$ was not constant, some sort of neural contribution would be indicated (Steen 1995). Investigation into this relationship between $L_{eq}$ and $E_{gl}$ showed that proportionality between the two was constant (Le Grand 1937).

Vos (1962) later found that linearity between $L_{eq}$ and $E_{gl}$ held in the peripheral retina but centrally there were deviations from exact linearity when luminance levels were low. Vos (1984) speculated that stray light sensitivity from the rods and the cones may differ meaning that changing from one threshold level to another could lead to a change from linearity.

This led to an investigation of the angular dependency of the equation above. The scatter function f(θ), was found to be inversely proportional to the square of the glare angle:

$$f(\theta) = k\theta^{-n} \qquad \text{(θ in degrees)}$$

n = scatter index, k = straylight coefficient. In the normal eye, n = 2 and k = 10.

This relationship is called the Stiles-Holladay relationship (Holladay 1926; Holladay 1927; Stiles 1929). The formula however does not hold up for every glare angle. It is satisfactory for angles above 2° but is not suitable for smaller angles than this (Fry 1965). At θ = 0 the Stiles-Holladay equation would predict an infinite amount of stray light to be produced where obviously it would have a finite value. Campbell and Gubisch (1966) examined straylight produced at very small angles using direct photometry of the retinal image.

Vos et al. (1976) linked data from this study with other available data to produce one complete function f(θ), which can be described by the following equation:

$$L_{eq}/E_{gl} = 10/(\theta + 0.02)^2 + 10/(\theta + 0.02)^3 + 10^6/e^{(\theta/0.02)^2} \tag{3.4}$$

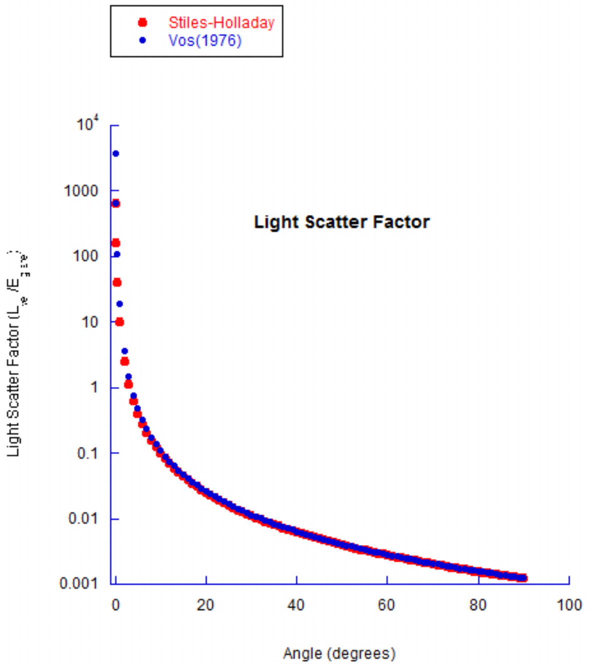



Figure 3.14 showing the comparison between the Stiles-Holladay equation and the equation developed by Vos (3.4). This is plotted using KaleidaGraph computer software, inputting values of glare angle in order to calculate the light scatter factor.

Vos (2003a) provided evidence to extend the Stiles-Holladay equation over the entire 0° to 100° range and introduced age and ocular pigmentation to the equation. The current CIE general DG equation is shown below:

$$\left({L_{veil}}/{E_{glare}}\right)_{general} = {10}/{\theta^3} + \left({5}/{\theta^2} + {0.1p}/{\theta}\right) \times \left(1 + (Age\ /\ 62.5)^4\right) + 0.0025p \qquad 3.5$$

Valid between $0.1<\theta<100$, in which $\theta$ is in degrees, $L_{veil}$ in $cd/m^2$ and $E_{glare}$ in lux. Note the switch from equivalent veiling luminance to veiling luminance due to new belief that the veil of light is due to entopic scatter and not just the luminance of the light that is visually identical to the amount of straylight. P is a value of ocular pigmentation ranging from 0 in very dark eyes to 1.3 in very light eyes (Vos 2003a).

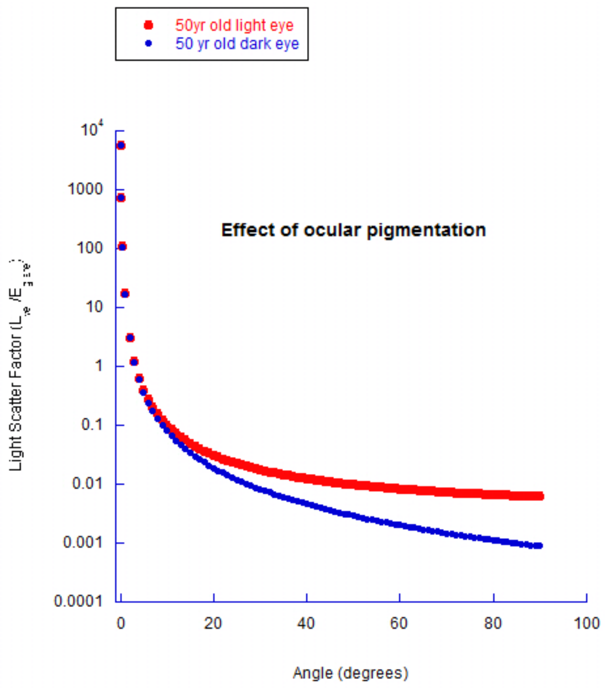



Figure 3.15 showing how the Light Scattering Factor alters with glare angle and ocular pigmentation according to equation 3.5.This is plotted using KaleidaGraph computer software, inputting values of glare angle in order to calculate the light scatter factor.

As sight problems associated with glare rarely deal with angles of less than one degree, another equation was also suggested called the CIE Age-Adjusted Stiles-Holladay Disability Glare Equation;

$$\left(L_{veil}/E_{glare}\right)_{Age\ related\ Stiles-Holladay} = 10\left(1+\left(Age/70\right)^{4}\right)1/\theta^{2} \qquad 3.6$$

This equation suggests that glare increases by a factor of two at 70 and a factor of three at 83 years old (Vos, 2003a).

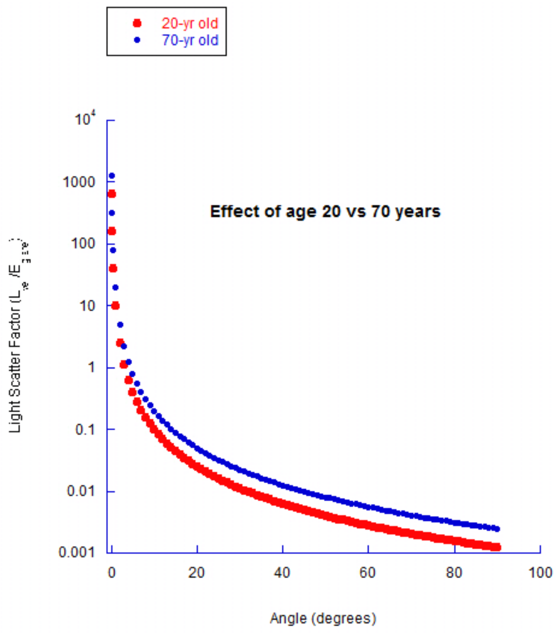



Figure 3.16 showing how Light Scatter Factor alters with glare angle and age according to equation 3.6. This is plotted using KaleidaGraph computer software, inputting values of glare angle in order to calculate the light scatter factor

As can be seen by the figures 3.14-3.16 above, all the expressions give very similar curves when plotting Light Scatter Factor against glare angle. The curves are so similar in fact that you cannot really tell the difference without plotting them together. The more recent expressions identify the differences caused by increasing age and changes in ocular pigmentation. The main deviations shown from the curves in figure 3.14 are due to iris colour (figure 3.15) or age (figure 3.16).

# 4.0 Vision and driving

## 4.1 Introduction

Intraocular light scatter, produced by different ocular structures is discussed extensively in chapter three of this thesis. Light can be scattered back to an observer and recorded using techniques such as the slit lamp, or the light scattered forward resulting in a reduction in visual performance can be measured using vision charts such as the Pelli-Robson or CSC. Both backward and forward light scatter have the potential to reduce visual performance, backward light scatter by reducing the amount of light reaching the fundus (Atchison and Smith 2000), forward light scatter by reducing the contrast of the retinal image (Allen and Vos 1967). This reduction in visual performance can lead to difficulty undertaking many day to day tasks, particularly when illumination levels are low, including reading, mobility and night driving (Elliott et al. 1996; Wood et al. 2012). Night driving is arguably the most serious situation that could be affected by the deficit in visual function caused by intraocular light scatter, endangering the lives of the affected individual and other road users alike.

Driving is a preferred mode of transport for many (Hu and Reuscher 2004), for both older and younger people alike (Collia et al. 2003). It is a visually demanding task (Owsley and McGwin 2010) and therefore adequate visual performance is necessary to help ensure the safety of the driver and other road users (Desapriya et al. 2011). Vision and its effect on driving performance is of importance to this project, however it should be noted at this stage that there are other factors to consider when examining driving performance and its social implications. Cognitive impairment has been shown to elevate crash risk and impair driving performance (Ball et al. 2006; Wood et al. 2008) and driving cessation has been found to reduce health related quality of life (DeCarlo et al. 2003), increase the likelihood of social isolation and depression (Fonda et al. 2001) and creates a need for improved public transport, especially in the more rural areas leading to greater expense (Rosenbloom 1993). All these factors need to be comprehensively considered when assessing driving performance and possible driving standards for cessation.

Many people report visual problems when driving at night. The majority of these complaints come from the general older population, not just from those with ocular disease (Mortimer and Fell 1989). The neural effect of reduced VA at lower luminance levels affects both the young and older populations, however the reduction is more pronounced with increasing age. Older people also have increased DG from oncoming car headlights due to the optical effect of increased light scatter (Mortimer and Fell 1989). The chance of being involved in a fatal collision is higher at night than during the daytime when considering distance driven, although there are a number of factors behind this. Increased speed, alcohol and fatigue as well as reduced visual performance at night all contribute to this statistic (Massie et al. 1995; Plainis and Murray 2002). Increased speed and the effects of alcohol account for the greatest number of fatal night time crashes and these tend to involve younger drivers (Owsley and McGwin 1999). Both younger and older drivers have been shown to have higher accident rates than the middle-aged population (Williams and Carsten 1989). Poor visibility under low luminance conditions has been shown to increase the likelihood of pedestrian or cyclist collisions (Owens and Sivak 1996) underlining the importance of acceptable night vision standards.

Despite this there does not seem to be any country in the World where night vision is comprehensively tested. In France good night vision is reportedly required and if this is found to be unacceptable a restricted daytime licence can be issued, however exact details of how this is measured is difficult to obtain (Bron et al. 2010). In Spain, restrictions can be made in the case of alterations to mesopic vision or glare but this must be determined according to undefined ophthalmologic criteria (Bron et al. 2010). In Germany, recommendations from the German Ophthalmological society have called for the Mesotest (described in chapter 4) to be used in assessment of night driving ability (Grosskopf et al. 1998), however this is yet to be implemented in the German assessment of driving standards.

Here in the UK, the National Institute for Health and Care Excellence and the Royal College of Ophthalmologists both refer to the Driver and Vehicle Licensing Agency (DVLA) when it comes to the information provided for driving standards. Glare and CS testing is mentioned only briefly. The DVLA state that in exceptional cases, when a licence has been revoked for a previous field defect, re-licensing can be considered for Group 1 drivers (car and motorcycle). This is possible if certain measures of visual function are met. These include un-impaired DG and CS, however there is no indication of what test or pass/fail level is to be used for this assessment (DVLA 2016a). Un-impaired DG and CS is also included as a pre-requisite for Group 2 drivers (lorry and bus), but again no indication of the exact requirements are included (DVLA 2016a).

Driving restriction throughout the World is largely based on VA and visual field assessment.

Table 4.1 Driving license requirement in Europe and selected US States (Bron et al. 2010).

| Country | VA | Visual field | Monocular vision | Other |
|---|---|---|---|---|
| EU | 6/12 in both eyes with corrective lenses | No less than 120° | 6/10 if monocular vision | Exceptions made by medical prof |
| UK | Number plate test, 6/12 | At least 120° horizontally (no sig loss within central 20° | Monocular vision if normal visual field | License revoked if standards not met |
| Germany | Corrected VA of 6/12 in best eye and 6/30 in worst | At least 120° horizontally (perfect within central 30°) | If monocular or worse eye below 6/30, better eye must be 6/10 | |
| France | Binocular acuity of 6/12 | 60° right and left. 30° above and below | If monocular or worse eye below 6/60, better eye must be 6/10 | Night vision necessary: can be exceptions for restricted daytime licenses |
| Spain | Corrected VA of 6/12 | Normal visual field | Monocular vision not allowed. Exceptions possible if better eye is 6/10 | Restrictions by medical experts |
| Italy | Corrected binocular VA of 6/6 | Normal field of vision 120° | Worst eye at least 6/30 | Sufficient chromatic sense and nocturnal vision |
| All US States | Most states 6/12 | Some states none, most 110°-140° | 6/12-6/30, 6/12 in most | Most states allow for restrictive licenses |
| California | 6/12 with correction if needed | No visual field requirement | Tested both monocularly and binocularly | Vision specialist can determine driving ability |
| New York | 6/12 in at least one eye with correction if needed | If VA between 6/12 and 6/24 must have 140° field of vision | | A vision specialist can determine restrictions |
| Iowa | At least 6/12 VA in one eye with correction if needed | 140° or better | | 6/12-6/15 no headlights driving. If 6/24 no driving over 35mph |

The Eyesight Working Group (2005) made recommendations for driving standard assessments in its report to the European Driving License Committee. The major findings from this report for Group 1 drivers (non-Heavy Goods vehicle or HGV) were as follows:

1) VA requirements should be formulated binocularly
2) The instructions for visual field assessment should be re-structured to include the vertical extension required, absence of central defects and the test method to be used
3) Requirements needed for twilight vision should be considered. Although no such test has been approved thus far, future introduction of these requirements is anticipated
4) Drivers should be diplopia free and requirements for this should be included
5) An adaption period is required after a newly developed eye disease
6) Restricted licenses should be considered
7) Further research regarding periodic screening should be conducted

As the average age of the general population increases there are a greater number of older drivers on our roads making up a larger percentage of total road users than ever before. They are also driving more miles per year than previous generations as car travel has become more common (Owsley et al. 2001). Visual impairment caused by normal ageing changes and/or pathological changes in later life are of particular importance. Links have been highlighted between visual impairment and crash involvement, perceived driving difficulties and poorer driving performance, both in simulator studies and driving on-road assessments (Owsley and McGwin 1999). Cataract, an extremely prevalent condition in the ageing population (Wang et al. 2000) compounds this issue further. Older drivers who had a history of crash involvement were 6 times as likely to have a serious CS deficit (< 1.25 log units) in both eyes due to cataract and three times more likely when the deficit was in just one eye (Owsley et al. 2001).

When looking at crash rate studies considerable variation exists in terms of crash classification and therefore these differences should be considered when assessing data presented. The type of crash can vary with respect to severity, for instance, was the crash the fault of the participant or was it a non-fault accident, was property damage or fatality the result (Owsley and McGwin 2010)? Also it is not advisable to use self-reported crash information (McGwin et al. 1998; Arthur et al. 2005) as there is a poor correlation between self-reported crashes and crashes on record where police reports were filed (Owsley and McGwin 2010).

### 4.2 Photopic Visual Acuity

Photopic VA is a measure of the ability of the eye to resolve fine detail at high luminance levels (Rubin et al. 2001) and is required for identifying pedestrians, road signs and signals and judging speeds and distances of other road users (Lachenmayr 2006). A measure of VA is used throughout Europe in driving standards assessment (Bron et al. 2010). In the UK a car or motorcycle license requires the correct identification of a car number plate (post September 1st 2001) from 20 metres, as well as a binocular VA of 6/12 Snellen in the testing room. These measures are made with optical correction in place if required (DVLA 2016b). The Esterman visual field test (described in section 4.7) is used to supplement this measure of VA, if there is eye or systemic disease present which could lead to visual field loss (DVLA 2016b). Bus and lorry drivers face more stringent vision standard requirements, although still based on VA and visual field measures (DVLA 2016b).

VA level has been shown to decline as we get older, although the point at which this starts to occur is not altogether clear. Elliott et al. (1995) indicated a gradual decline in VA from the age of 30 onwards, whereas others suggest this doesn’t happen until the age of 50-60 years (Weale 1975; Adams et al. 1988; Mortimer and Fell 1989) or even later (Haegerstrom-Portnoy et al. 1999). Elliott et al. (1995) used a logMAR chart (figure 4.1) to test best corrected VA, whereas other earlier studies used Snellen or other measures of VA, likely to be less accurate and providing truncated results. LogMAR charts have been shown to be more reliable than Snellen charts (Lovie-Kitchin 1988), and more sensitive to change (Bailey et al. 1991). Haegerstrom-Portnoy et al. (1999) did use a logMAR chart to measure VA albeit habitually, and did not screen participants for ocular pathology. It is therefore likely VA gradually deteriorates from approximately 30 years of age (Elliott et al. 1995), but this effect becomes more pronounced later in life especially with pathology present (Haegerstrom-Portnoy et al. 1999).

Although research has conclusively identified a reduction in VA with age, from a clinical perspective this reduction is negligible in the older healthy eye. Even in those 75 + years and older, VA has been shown to be approximately 6/6 Snellen (Elliott et al. 1995), A level which is well within the vision standards for driving here in the UK.

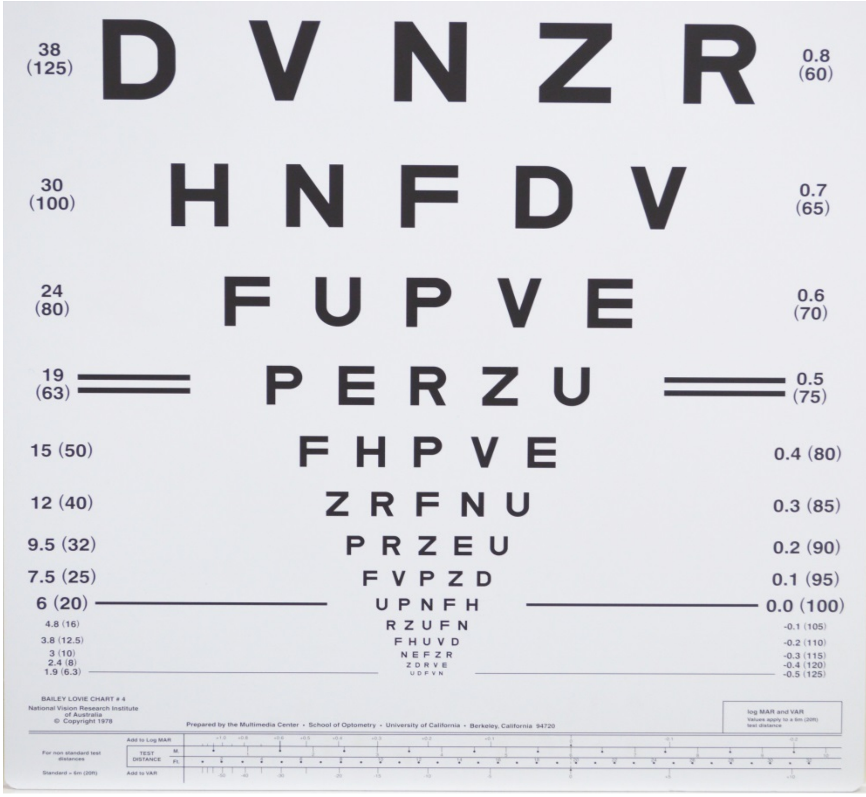



Figure 4.1 showing a logMAR chart for VA assessment.

The earliest research into the effect of VA on motor vehicle crash rates found no association between poor VA and collisions in young and middle aged drivers although a weak significant relationship was seen with older drivers (Hills and Burg 1977). This weak yet significant relationship has also been seen in later studies (Marottoli et al. 1998; Ivers et al. 1999). However there is at least as much evidence to suggest that no such relationship between VA and collision rate exists (McCloskey et al. 1994; Owsley et al. 1998a; Owsley et al. 2001). Visually impaired people tend to drive less miles and in more familiar surroundings than their normal sighted counterparts (Ball et al. 1998; Freeman et al. 2005) and if this finding was not considered in certain studies it may explain the differences seen. Two more recent, well designed, large sample size studies also found no significant association between VA and vehicle crash rates (Rubin et al. 2007; Cross et al. 2009).

Actual driving performance, whether simulated or real life, is an additional point of interest when considering the difficulties caused by impaired visual function. It may actually contribute more meaningful information than crash rate figures as confounding factors are more limited. Work in this area has been less extensive. Optical blur induced by the addition of positive lenses on a closed road course has been shown to reduce the ability to recognise road signs and impair road hazard avoidance, although the ability to navigate a vehicle through the course was unaffected (Higgins et al. 1998; Wood and Owens 2005; Wood et al. 2012). When considering subjective driving difficulty under all conditions and comparing this to photopic VA, a strong significant correlation was found. However, the correlation with perceived driving difficulty at night was not significant (van Rijn et al. 2002).

The correlation with driver crash rates and photopic VA is at best a weak one (Charman 1997) yet in performance based studies, impairment with refractive blur has been demonstrated. Higgins and Wood (2005) found a linear reduction in sign recognition, hazard avoidance and total driving time to complete a closed road circuit with increasing amounts of induced optical blur. Optical blur reducing VA to 6/60 was found to impair driving performance to a similar level as mild cataract simulation, reducing VA to 6/12.

One consideration when discussing driver performance studies would be the fewer confounding factors involved. Every participant does the same task and therefore the issues of familiar surroundings and driving exposure is of no real importance. Another factor would be that VA does not measure the skills necessary for driving performance. VA testing, designed to limit distractions and secondary task demands is not well suited to driving where both central, peripheral and sudden unexpected moving targets are seen (Owsley and McGwin 2010). Road sign recognition although necessary for activities like route planning may not be important in collision avoidance (Owsley and McGwin 2010). Such conclusions may indicate that VA is not the best test of visual function when assessing driving safety and performance.

### 4.3 Mesopic Visual Acuity

Mesopic VA involves the measurement of acuity under twilight conditions (0.001 to 3cd/m$^2$) (Charman 1996). On well illuminated roads, luminance levels of approximately 1cd/m$^2$ are commonly found (Charman 1996; Ekrias et al. 2008). Values as low as 0.1cd/m$^2$ have been found on wet country lanes when illuminated solely by car headlights (Chauhan and Charman 1993). In both situations, road luminance conditions at night fall into the mesopic luminance range, never falling to scotopic levels (< 0.001cd/m$^2$).

Mesopic VA falls as illumination decreases (Mortimer and Fell 1989; Mainster and Timberlake 2003). Sturr et al. (1990) was able to show in both the healthy young and older eye that VA fell from approximately Snellen 6/5 in photopic conditions to Snellen 6/10 at mesopic luminance levels, falling to around half of the photopic VA level (Lachenmayr 2006). The loss in mesopic VA is more pronounced in the older population (Mortimer and Fell 1989; Puell et al. 2004) at least in some part due to the changes seen in pupil size and to the ocular media throughout ageing. Puell et al. (2004) reported that this decline starts after 50 years of age.

Few studies exist that investigate mesopic VA levels and specific driving tasks (Gruber et al. 2013) and therefore there is scope for further investigation into this measure of visual function. Drivers who were involved in collisions at night were more likely to have reduced mesopic acuity levels when compared to those with clean driving records (Lachenmayr et al. 1998). Correlations have been identified between mesopic acuity levels and perceived driving difficulty at night (van Rijn et al. 2002) and between mesopic VA and reduced target identification distances (Sivak and Olson 1982). Therefore, from the little literature available, mesopic VA may be a better alternative to photopic VA when assessing night driving safety.

### 4.4 Scotopic Visual Acuity

When driving, luminance levels are normally in the higher mesopic range where both the rods and cones are active (Charman 1996). Scotopic levels where only the rods are active are very rarely seen because normal road lighting, car headlights and oncoming car headlights, shift night road luminance levels into the mesopic luminance range (Aulhorn and Harms 1970; Eloholma et al. 2006).

### 4.5 Contrast sensitivity

Unlike measures of photopic VA, CS is not used in any form for assessing driver suitability in the UK. Research into its role on driver performance and safety is less extensive than for VA but still as mixed in its conclusions. When considering the effects of CS on crash history, Ball et al. (1993) found CS impairment to be associated with recent crash involvement. Hennessy and Janke (2009) examined CS as a screening test for licensure renewal where people who failed were more likely to have future crash involvement. However results from Rubin et al. (2007) and Cross et al. (2009) both showed no link between CS impairment and the likelihood of having future crashes.

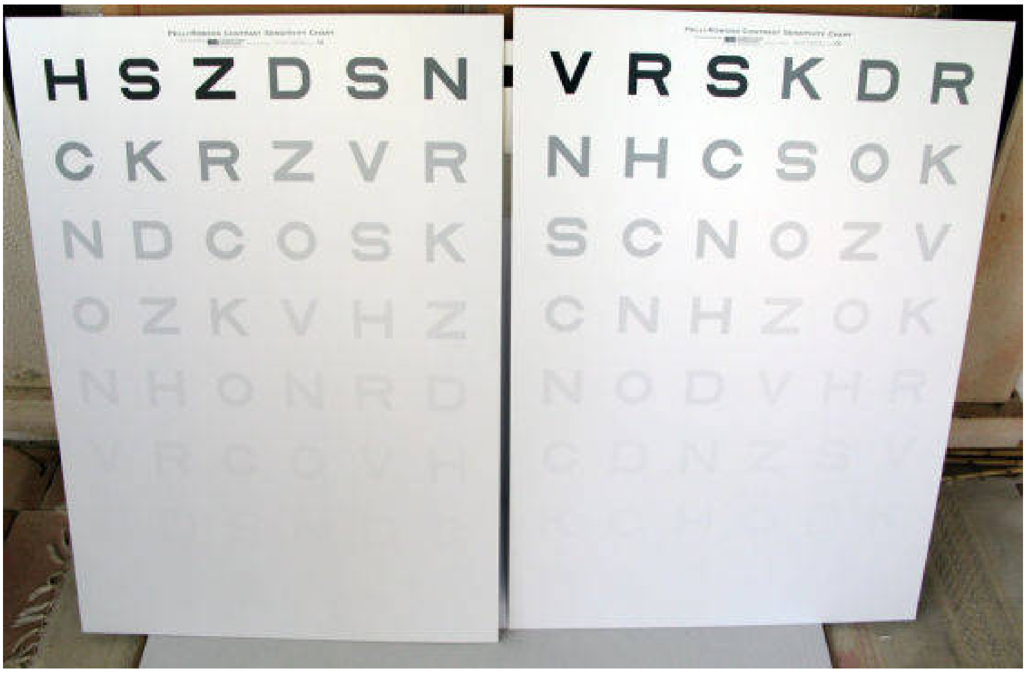



Figure 4.2 showing the Pelli-Robson chart.

When the focus of CS impairment is switched to people who have cataract, strong associations have been shown. Cataractous patients with CS deficit in both eyes examined using the Pelli-Robson chart, were found to be six times more likely to have had recent crash involvement. Even when the reduced CS was found in just one eye they were found to be three times as likely as those without impairment (Owsley et al. 2001). In the same cohort, those who had cataract operations to improve their vision, reduced their risk of future crashes by 50% compared to those who did not elect for surgery (Owsley et al. 2002). The strong relationships found here with recent crash history that were not found elsewhere, can almost certainly be attributed to the patient cohort. CS is reduced as we age and deteriorates further with cataract (Rubin et al. 1993; Mäntyjärvi and Laitinen 2001). Therefore, there would be a much greater representation of CS impairment in cataract patient studies than in population based studies (Rubin et al. 2007; Cross et al. 2009). The Pelli-Robson was used to measure CS in the aforementioned studies. Also as is the case with impaired VA those with a CS deficit may self-limit the amount of driving undertaken. Several studies have shown significant relationships between impaired CS and driving modification or difficulty (Ball et al. 1998; McGwin et al. 2000; Freeman et al. 2005).

When examining the relationship between driving performance and CS impairment, results appear to give a more consistent picture than do the crash rate studies. When using simulated CS impairment (Wood and Troutbeck 1995) on a closed road circuit, superior driving scores were correlated to improved CS. Others have found that CS is better predictor of road sign recognition and pedestrian avoidance than photopic VA (Anderson and Holliday 1995; Wood and Owens 2005; Wood et al. 2012). An improvement in driving performance was also observed after cataract surgery - a factor attributed to increased CS after the operation (Wood and Carberry 2004). CS has been shown to give extra information over photopic VA when assessing cataract patient's (Elliott and Hurst 1990; Shandiz et al. 2011; van Rijn et al. 2011). There is a greater likelihood of someone with reduced CS failing to read a number plate from 20m (a requirement in the UK), even if they manage to reach the required VA standard of Snellen 6/12 in the testing room (Rae et al. 2016). This finding would further indicate that in those with ocular pathology such as cataract, CS should also be considered for driving standard assessment.

### 4.6 Disability glare

As previously mentioned glare is normally split into two main classifications, that of discomfort glare and DG. Discomfort glare is an annoyance or distracting effect caused by a peripheral light source that doesn't necessarily affect visual function whereas DG leads to a reduction in the contrast of retinal images making objects harder to perceive (Abrahamsson and Sjostrand 1986; Mainster and Timberlake 2003; Vos 2003a). Once again, results in the literature are mixed when assessing the association between DG and the likelihood of having a motor vehicle collision. Increased crash risk with increased DG has been shown (Lachenmayr et al. 1998; Rubin et al. 2007) although other studies have found no such relationship (Ball et al. 1993; Owsley et al. 2001) or even the reverse, where slightly increased DG in those who were minimally affected by glare reduced the likelihood of crash involvement (Rubin et al. 2007). Ball et al. (1993) used the Vistech MCT 8000 to measure DG, a device shown to have its limitations (Elliott and Bullimore 1993). Owsley et al. (2001) and (Rubin et al. 2007) both used the Pelli-Robson chart in conjunction with the Brightness acuity tester (BAT) to measure DG. In the Owsley study participants were dichotomized into two groups, those with a DG score of over 0.25 log units or five missed letters and those less affected. This would explain the differences seen in this study compared to the one by Rubin and colleagues (2007) as subtle differences may have been missed in the Owsley (2001) study.

It is unclear exactly what would cause these divergent findings. In some cases it could be put down to the difficulties in exactly defining the term glare and poor understanding by what is meant by the term, particularly in subjective studies using questionnaire responses. van Rijn et al. (2002) found a significant relationship between DG and perceived driving difficulties at night although (McGwin et al. 2000) found no such association. Another consideration would be how DG was measured. In most of the studies above, DG was measured monocularly. For most people driving is a binocular task and therefore it would appear strange to assess DG effects monocularly. This measurement is further questioned when we consider possible binocular summation and inhibition effects (Pardhan and Elliott 1991; Pardhan and Gilchrist 1991; Longley and Whitaker 2015). Also DG is a measure of CS both with and without a glare source and therefore if someone already had a reduced measure of CS due to pathology other than lens or corneal changes, DG may well be artificially reduced. This is because the amount of DG that a person experiences is normally calculated as the CS level with the glare source, subtracted from the CS level without the glare source. This is an accurate way to establish the difference glare makes to vision and particularly useful when establishing when a cataract should be removed for example. However when using this measure in relation to crash rates or driving performance a measure of CS in the presence of glare may be more informative for purpose as it gives a better idea of overall visual performance found when driving.  CS scores measured in the presence of glare have previously been shown to be superior to DG scores when assessing cataract patients with normal neural function (Elliott et al. 1991b; Elliott and Bullimore 1993). When using the Pelli-Robson chart, CS without glare scores in cataract patients are already reduced due to wide angle scatter and the BAT only increases this effect slightly. This reduces the useful information that can be generated from DG scores when compared to CS with glare scores (Elliott and Bullimore 1993).

As mentioned previously mesopic VA has been shown to deteriorate after the age of 50. In the same study mesopic VA in the presence of glare was found to deteriorate from the age of 40 (Puell et al. 2004). Therefore glare leads to earlier and greater age-dependent deterioration in mesopic vision than in a no-glare situation (Puell et al. 2004). This is a similar finding to CS recordings (Mäntyjärvi and Laitinen 2001), DG (Elliott and Bullimore 1993) and intraocular light scatter or straylight (van den Berg et al. 2009b) results, where there is a gradual reduction in all visual functions with increasing age, further exaggerated when cataractous changes are present. The time required to recover from a glare source also increases with age (Morgan and King 1995). This is due to a substantial decline in macula function as we get older affecting the rate of photo pigment regeneration (Elliott and Whitaker 1991).

Driver performance under the influence of glare is again more conclusive in its results than driver safety studies. Using simulated blur and cataract impairment to a mean photopic VA level of 6/12, Wood et al. (2012) investigated pedestrian detection at night with and without glare on a closed road circuit (figure 4.3). Significantly fewer pedestrians were identified by the simulated cataract group than by the ‘normal’ and ‘blur’ groups, a finding further exaggerated when a glare source was present. This highlights the limitations of solely using a photopic VA measure to assess visual function whilst driving at night. The cataract simulators had a significantly greater effect on CS and DG measures than they did on VA as is the case with normal cataractous changes. The blurred group (VA 6/12) had significantly inferior VA and CS levels than the normal (VA 6/5) group but the difference in DG was not significant (Wood et al. 2012).

When averaged across all groups of visual function, glare significantly impacted on the distance of pedestrian identification (Wood et al. 2012). Figure 4.4 shows how simulated blur and simulated cataract affected the distance at which pedestrians, wearing different types of clothing, were identified. This was investigated both with and without a glare source present. Both simulated blur and simulated cataract had a huge impact on this distance when compared to normal subjects, with simulated cataract once again causing the greatest deficit in performance. Figure 4.4 also serves to highlight how pedestrians can attempt to make themselves as visible as possible under low luminance conditions. However, even if these steps are taken, those with cataract may still struggle to recognise pedestrians until it may be too late. These findings are in agreement with Theeuwes et al. (2002) who found that the ability to spot simulated pedestrians at the side of the road was significantly reduced even when the illuminance of the glare source was at low levels and Ranney et al. (2000) showed similar findings using a driving simulator. On dark and winding roads driver speed has been found to reduce, a factor which is more pronounced in the elderly (Theeuwes et al. 2002) and sign legibility under the effects of glare is diminished in the older driver (Schieber and Kline 1994).

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This showed that normal participants recognised a greater percentage of pedestrians than blurred or cataractous participants when a glare source was present. This image can be found in the paper referenced below.

Figure 4.3 showing the percentage of pedestrians recognised as a function of driver visual status and glare condition (Wood et al. 2012). Three groups were used, those with normal vision (VA 6/5), those blurred to an approximate VA of 6/12 and those with cataract simulators, again with an approximate VA of 6/12. Glare was introduced using battery powered halogen headlights, positioned to imitate the position of an oncoming vehicle.

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This diagram showed the distance at which pedestrians were correctly identified whilst wearing different types of clothing by the groups of participants tested. This was done in this instance without glare. This diagram can be found in the paper referenced below (see figure legend).

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This diagram showed the same thing as the diagram described previously but this time in the presence of glare. Again this diagram can be found in the paper referenced below.

Figure 4.4 showing the mean distances at which drivers responded to the presence of a pedestrian as a function of the visual status of the drivers and pedestrian clothing in absence (top) and with (bottom) glare (Wood et al., 2012). The pedestrian clothing worn is indicated in the legend (top right of the figures a + b). In the black condition the pedestrians wore a black sweatshirt. In the vest condition pedestrians wore the original black sweatshirt with a silver retroreflective panel measuring $1325cm^2$ on their chest. In the bio condition pedestrians wore the original black sweatshirt but this time with 50mm wide strips of the silver retroreflective fabric around the wrist, ankles, elbows, knees, shoulders and waist. Glare was introduced using two battery powered halogen headlights positioned to imitate an oncoming vehicle.

## 4.7 Visual Fields

Visual fields are used in the UK as a measure of driving standards. They are not performed on everyone, but rather where there is reason to suspect visual field could be compromised. In such instances the Esterman binocular visual field test is used where a patient needs to have a visual field of 120° horizontally and at least 20° above and below the horizontal midline with no significant defect within this area. This is however not a universal measure of required visual field as many places and countries use different visual field requirements with no obvious explanation as to why (Owsley and McGwin 2010).

Once again, studies which have looked at the implications of visual field defects have found mixed results when it comes to crash histories. In an early study involving 10000 participants which accounted for driving exposure, severe binocular visual field loss was significantly linked to crash and violation rates when compared to unaffected drivers (Johnson and Keltner 1983). This is supported by other studies that have shown similar findings (McGwin et al. 2005; Rubin et al. 2007). In equal measure however, there are those who have found no association between visual field loss and traffic violation rates, both in studies that accounted for driver exposure (Hu et al. 1997; Owsley et al. 1998a) and in those that did not (Council and Allen 1974). People with Glaucoma were shown to be five times more likely to be involved in motor vehicle collisions than normal drivers (Haymes et al. 2007). When these results were adjusted for visual field impairment, the Glaucoma group still had elevated crash risk, indicating some factor other than visual field defect was at least somewhat responsible for the finding. More recently Kwon et al. (2016) have also shown an increased crash risk in the Glaucomatous population and this increase was independent of VA or CS changes.

It is however difficult to fully compare the results mentioned above due to no real standardization as to what constitutes an impaired visual field. Some studies have concentrated on binocular field loss (Johnson and Keltner 1983; Rubin et al. 2007) the first of which mentioned severe binocular field loss yet did not quantify exactly what this meant. Another study, found the strongest association with field loss in the worse of the two eyes (McGwin et al. 2005).

Other publications have concentrated on people with and without Glaucoma (Owsley et al. 1998b; Haymes et al. 2007) a condition by its nature that causes visual field deficit but to very differing extents in different people. In future studies it would therefore seem important to clearly describe what classification was used to define an "impaired visual field."

The relationship between driving performance and visual field assessment has also been examined, although more sparsely. Simulated visual field loss has been used to investigate both on and off road driving. It was found to hinder sign and obstacle identification and also to lengthen reaction times but not affect speed estimation and stopping distances (Wood and Troutbeck 1992; Wood et al. 1993; Wood and Troutbeck 1995). Simulated visual field defects, particularly in the superior field have also been found to affect hazard perception when using a driving simulator (Glen et al. 2015). However results from simulated visual field loss studies should be treated with caution. Sudden field changes may not be a good representation of how someone whose visual field loss has gradually developed over time deals with a task like driving. Such an individual may well develop compensatory mechanisms to help deal with the situation. Also closed course or simulated driving is less complex than in the real world and may not well identify those most at risk when more information needs to be processed more quickly. It therefore remains to be seen if simulated or off road studies are reliable and valid measures of driving safety (Owsley and McGwin 2010).

### 4.8 Useful field of vision (UFOV)

The task of driving takes place in a visually cluttered environment, involving both central and peripheral vision to safely get where we need to be. This environment is constantly changing and we are often unsure of exactly when we will need to adapt to a visual stimuli. These demands have prompted researches to investigate the link between driver safety, performance and driver attention skills (Owsley and McGwin 2010). The role of driver attention on safety was largely ignored until the 1990's but even before this there was substantive evidence to suggest that older people even in the absence of dementia, had poorer visual divided attention abilities with briefly present stimuli, than their younger counterparts (Sekuler and Ball 1986; Ball et al. 1988; Allen et al. 1994). These deficits in the older population were then linked to possible driving implications (Ball et al. 1990a).

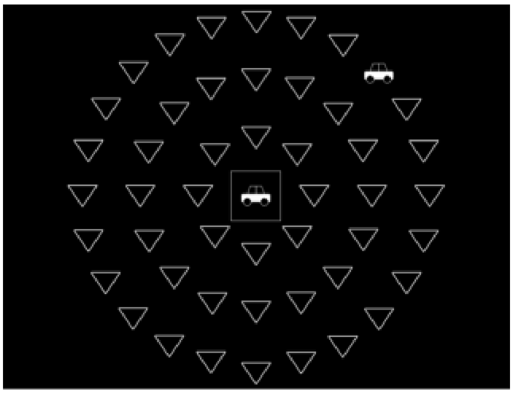

Figure 4.5 showing the UFOV test. The task for the participant is to identify a central target while at the same time localising a more peripheral stimulus. This can be done with or without additional distractor stimuli.

The UFOV seen in figure 4.5, is defined as the total visual area in which information can be acquired within one eye fixation i.e. without eye or head movements (Ball et al. 1988). It is measured binocularly and gives an estimation of the time needed to discriminate or identify a central target while at the same time localising a more peripheral target further complicated, in some conditions, with additional distractor stimuli (Owsley and McGwin 2010; Gruber et al. 2013). It therefore uses a more complex visual background than does a normal visual field test (Ball et al. 1988). Since its inception people with impaired UFOV results have been shown to be more likely to report driving problems (Ball et al. 1990b). Also there is substantive literature to suggest the impairments seen on the UFOV is indicative of recent crash history (Sims et al. 1998; Sims et al. 2000; Clay et al. 2005; Ball et al. 2006; Rubin et al. 2007; Cross et al. 2009) and subsequent crash involvement (Owsley et al. 1998b). These findings translate to driving performance where divided attention deficits are associated with impaired sign and pedestrian identification and people with such deficits required more time to complete the closed road circuit (Wood et al. 1993). It should be noted that the vast majority of this literature comes from the team who were involved in the inception of the UFOV test and therefore results need to be corroborated by others before definitive conclusions can be made. One study involving the UFOV and perceived driving difficulty found significant correlations for daytime driving but perceived driving difficulty at night showed no correlation (van Rijn et al. 2002).

### 4.9 Conclusion

Photopic VA is currently the most widely used test for assessing fitness to drive around the world. As previously described in section 4.2 the current visual driving standards in the UK involve a measure of VA and in some people an additional visual field assessment. Detailed information can be found in the

DVLA report entitled: Assessing fitness to drive – a guide for medical professionals (DVLA 2016a). In France and Spain restricted driving licenses can be awarded if night vision is restricted although no details regarding classification for this are not readily available (Bron et al. 2010).

Photopic VA measures are commonly used in assessment of driving standards despite the fact that correlations between driving performance and safety are at best weak for both day and night driving (Owsley and McGwin 2010; Desapriya et al. 2011). The use of photopic VA in this manner is unlikely to change because of the public acceptance of the importance of VA for tasks like road sign legibility (Owsley and McGwin 2010). A more realistic approach would be to supplement the test of VA with other measures of visual function such as CS, DG, mesopic VA, visual field and divided attention tasks like the UFOV, as there is significant weight linking all these measures of visual function to driver safety or performance, whether during the day or at night. Before this can be achieved, well designed large-scale prospective studies need to be designed where these tests of visual function can be examined both on their own and in combination as to their effectiveness in predicting driver safety and performance.

### 4.10 Countermeasures for glare

Despite the problems many people face from discomfort and DG, available countermeasures to combat this problem are few and far between. The most effective method would involve the implementation of road lighting to the whole road network. However, the cost of implementing such a scheme would likely prevent this from happening. Drivers are reported to feel more comfortable on illuminated roads (Mace et al. 2001) and DG is reduced. Road lighting has also been shown by some to reduce night-time crash rates (Plainis and Murray 2002; Makela and Karki 2004) but not all (Steinbach et al. 2015). The difference seen here may be explained by the severity of collision. Jackett and Frith (2013) found a significant relationship between average road luminance and safety, with the indication that a stronger relationship is found between lower road luminance and more serious accidents. Glare screens have also been proposed where a screen is placed between the two lanes of a dual carriageway or motorway preventing car headlights from the opposing carriageway being seen. Again the cost of any such scheme and the fact it couldn't be used on single lane roads where the need is greatest would limit its usefulness. Polarized headlight systems are arguably the best possible solution but again are unlikely to be implemented because of cost (Rea et al. 2010).

Filters have been thought to improve visual performance by reducing the luminance of a glare source or selectively absorbing certain wavelengths which are scattered preferentially in the eye (Steen 1995). It has often been stated that intraocular light scatter is wavelength dependent, with shorter wavelengths being scattered more (Leat et al. 1990), hence following the Rayleigh theory of light scatter. This is the reason why yellow filters are sometimes recommended to people with low vision. Eperjesi and Agelis (2011) investigated the effects of three commercial yellow filters to see if they generated an improvement to VA and CS with and without glare in healthy eyes. The data generated from this study from the 55 patients tested showed that yellow filters do not have a beneficial effect on deleterious visual effects of forward light scatter, caused by cataract. It was concluded they had a negative but not clinically significant effect on VA, CS (with and without glare) and reading (without glare) under forward light scatter conditions. It is believed that these negative effects were probably due to a reduction in retinal illuminance. This is similar to the findings of (Steen et al. 1993) that coloured filters had no effect on the amount of DG produced. Coloured windscreens, spectacles or IOLs reduce the retinal illumination of the subject and so hinder vision in a night time environment, especially when they reduce the amount of violet or blue light needed for mesopic and scotopic vision (Mace et al. 2001; Mainster and Timberlake 2003; Mainster and Turner 2010).

Headlamp height and size is another consideration in attempts to reduce problems from glare. Increasing the size of the headlights has been shown to reduce the amount of perceived discomfort glare. This is attributed to the fact that as the light gets larger in size the luminance is reduced in order to produce the same illuminance at the eye. Changing the size of the headlights has been shown to have no effect on the amount of DG experienced (Mace et al. 2001; Van Derlofske et al. 2004). The height of a headlamp system has been shown to affect both discomfort and DG where, if the height is increased, more glare is experienced. Reaction times are increased and detection distances reduced. The larger effect from headlamp height appears to be on discomfort glare rather than DG (Akashi et al. 2008). In order to reduce glare as much as possible it is also important that headlights are not miss-aligned (Locher and Kley 2010), optimum correction is worn, timely cataract operations performed (Wood et al. 2012) and headlamps, glasses and windscreens are free from dirt or scratches (Mace et al. 2001; Vos 2003a). The possibility of night driving licensure restriction and/or education and self-restriction should be considered (Mace et al. 2001; The Eyesight Working Group 2005).

## 5.0 Glare Testers

### 5.1 Introduction

Elliott and Bullimore (1993) outlined criteria by which glare tests should be judged: They should be valid in that they measure what they purport to measure. They should be able to discriminate between “normal” patients and those with cataract or other media anomalies. They should also be repeatable (Aslam and Patton 2005). Repeatability is a measure of the variability of measurements taken from a single person undergoing the same task under the same conditions. Many DG tests are simple in concept in the way they attempt to assess vision in the presence of a glare source.

Elliott and Bullimore (1993) supported the criteria for clinical vision test design suggested by an American Academy of Ophthalmology (AAO) report:

The test should be a forced-choice psychophysical method.

Test targets should follow a uniform logarithmic progression.

Several trials should be used at each level of acuity or contrast.

The AAO suggested that tests should ideally be forced-choice to minimise errors based on differences in patient attitudes rather than visual abilities (Higgins et al. 1984; Rubin 1990).

There are several practical problems related to DG testing. Firstly the angle and distance of the glare source from the eye is a critical feature to standardize (Whitaker et al. 1994). Many early studies used a point source of light as a glare source. This meant that the light was usually at different distances from various parts of the test and hence the angle θ was not constant. The difficulty of the task would therefore be affected. A point light source can also attract a patient's fixation leading to the possibility of afterimages. Any readings obtained using a point light source could therefore involve both DG and glare recovery components (Rubin 1995). Glare tests should not have stimuli at too low a luminance as the increased retinal illuminance from straylight may even improve visual performance (Whitaker et al., 1994). Pupil size changes could also be an issue. If the glare source was situated very close to the eye the additional pupil constriction caused may improve the visual performance of certain people (Tan et al. 1998; Wachler et al. 1999) or reduce it in others.

Pelli and Tillman (2008) stated that if many closely spaced symbols or letters are present, people with central field loss or strabismic amblyopes could be affected by crowding and therefore it may be better to show a single stimulus.

Glare testers are still not widely used in the UK, either in the decision to perform cataract surgery or for driving standards purposes. This is despite the substantive weight of evidence to suggest that VA is not a good predictor of visual function in people with cataract, where people can retain good levels of VA but have significantly impaired CS or glare sensitivity (Elliott 1993; Elliott et al. 1996). People with cataract have also been found to have increased DG measures (Elliott and Bullimore 1993; van Rijn et al. 2005; van den Berg et al. 2009b), be more likely to have recent crash involvement (Rubin et al. 2007) and have impaired driving performance (Wood et al. 2012). In a study performed in 2000 involving 473 questionnaire responses from Ophthalmologists working in the UK it was found that only 12% of surgeons were regularly using DG measures on their cataract patients and most of these were found to be using a pen torch or an angle poise lamp as a glare source (Frost and Sparrow 2000). It was previously proposed that a lack of standardisation, familiarity, lack of scientific validity, poor correlations with symptoms and cost are the likely reasons glare tests were not more widely used (Koch and Liu 1990).

### 5.2 Early glare testers

The most basic of all glare tests involve a point glare source at a given distance and angle to the eye. Examples of which would include a measure of visual function such as VA or CS with and without a pen torch or angle poise lamp acting as a glare source. This method is quick and easy to perform. It is also a cheap way of attempting to establish how much someone is affected by glare and because of these reasons is one of the more common ways DG was assessed by ophthalmologists (Frost and Sparrow 2000). The problem with this method is standardisation. Both the distance and angle of the glare source from the eye could be measured if enough time was available but the luminance of the glare source would be very hard to standardize in every testing room. As previously discussed, all these factors would have an impact on the amount of veiling luminance produced (Vos 2003a) and especially in a busy testing room environment where it is unlikely there would be time to measure distance and angle from the patient. This method is still the cheapest, most understandable and accessible form of glare testing but its lack of standardization is likely one of the main reasons why glare testing was used rarely (Koch and Liu 1990).

In order to try and more easily standardise glare source distance and angle, devices were established to give greater control over these factors. The Vistech

MCT 8000 shown in figure 5.1 (Vistech consultants) (Ginsburg et al. 1987), the Miller-Nadler glare tester shown in figure 5.2 (LeClaire et al. 1982) and the Berkeley glare test shown in figure 5.3 (Bailey and Bullimore 1991) were all developed over a 20 year period and each attempted to have set working distances and glare angles for measurements puposes.


Figure 5.1 showing the Vistech MCT8000.

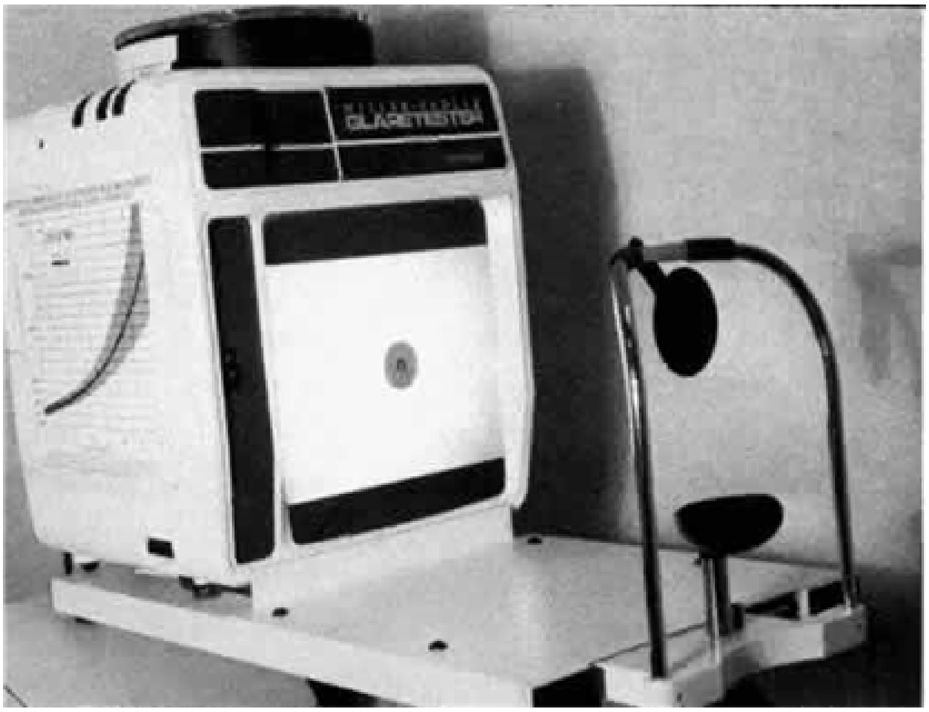


Figure 5.2 showing the Miller-Nadler glare tester.

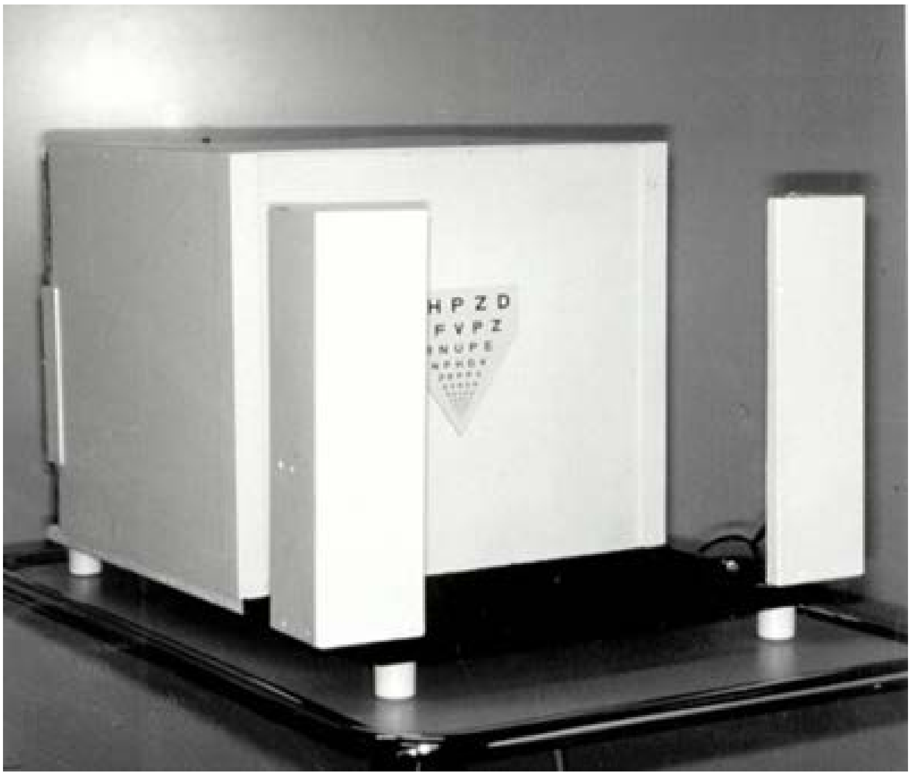

Figure 5.3 showing the Berkeley glare tester (Niesen et al. 1997).

The Miller-Nadler and the MCT 8000 used measures of CS with and without a glare source whereas the Berkeley used a measure of either high or low contrast VA with and without glare. Despite these changes the MCT 8000 and the Miller-Nadler glare testers were found to give poor discriminative ability between participants with and without cataract and poor repeatability (Elliott and Bullimore 1993). It was suggested that this was most likely down to the lack of a geometric progression between different contrast levels in these devices (Elliott and Bullimore 1993). In the same study, the Berkeley test was found to be a repeatable, discriminative and valid measure in comparison. However, the bulky size of the device and the fact that if the luminance of the glare source were to fall over time the test would become easier are probably the main reasons this device was never widely used.

### 5.3 Commercially available glare testers

The brightness acuity tester (BAT) (Marco Ltd) (Holladay et al. 1987) shown in figure 5.4, was developed at a similar time to the devices mentioned above but has better stood the test of time, probably down to its relatively cheap cost and its greater portability. The device itself consists of an internally illuminated hemispherical bowl which is held close to the eye which acts as the glare source. At the centre of which lies a 12mm aperture through which the VA or CS chart being used with the device can be viewed. The device itself has probably been the most widely used in the research world to date (Holladay et al. 1987; Elliott and Bullimore 1993; Tan et al. 1998; Wachler et al. 1999; Owsley et al. 2001; Rubin et al. 2007) and was previously shown to be the most widely used specifically designed glare tester in hospital eye departments in the UK (Frost and Sparrow 2000). Despite this, it was still only used by approximately 1.4% of surgeons (Frost and Sparrow 2000). The BAT has been shown to be a repeatable and discriminative measure of DG with the use of Regan or Pelli-Robson charts (Elliott and Bullimore 1993) although still suffers from the problem of standardizing glare source luminance. The device has three luminance settings and has a rechargeable set up where the luminance of the glare source falls if the device is lacking charge. It is also unlikely that every test chart in every testing room will be illuminated to exactly the same level. This means that the difficulty of performing the task is unlikely to be equally difficult over time. At its highest luminance setting the BAT has been shown to overestimate DG (Prager et al. 1989).


Figure 5.4 showing the brightness acuity tester (BAT).

The CSV-1000 (VectorVision, US) shown in figure 5.5, was first developed in 1991 in order to assess CS and VA. Since then it has been widely used in research for the assessment of visual function and has been shown to be a repeatable measure (Schmitz et al. 2000; Jiménez-Alfaro et al. 2001; Packer et al. 2002; Quesnel et al. 2004). The test is internally illuminated, calibrated to produce a luminance of 85cd/m$^2$. The chart measures CS at 3, 6, 12, and 18cpd using sine wave gratings. The highest contrast gratings are found towards the left of the screen and reduce in contrast as they move across to the right. The task for the participant is to identify, in each of the eight positions, whether the grating appears on the top or bottom row for each spatial frequency used A, B, C, or D (figure 5.5). This provides a 2-AFC testing method, more prone to guessing than devices which incorporate more response choices such as letter charts (Richman et al. 2013). The contrast level of the last correct response is normally taken as contrast threshold (Pandita et al. 2007). Two halogen bulbs are positioned at each side of the console to assess the effects of glare on CS (Pandita et al. 2007). The device is also reasonably expensive to purchase.

Figure 5.5 showing the Vector Vision CSV 1000, used to measure CS with or without glare. CS can be tested at five different spatial frequencies and at eight different CS levels.

The Takagi contrast glare tester, CGT-1000 (Takagi Seiko Co Ltd) shown in figure 5.7, was developed more recently as a glare tester for measuring CS and glare in pre and post-operative cataract patients. It is a self-contained unit and allows measurement of CS at six different target sizes, at 13 different contrast levels with an average step size of 0.15 log units. The stimulus duration can also be controlled. The stimulus and glare source used by this device is shown in figure 5.6. Glare testing is done in the same manner but with a ring of LED lights surrounding the target and can be completed at three different luminance intensities. The illuminance of the screen and at the eye is monitored by an internally built photometer (Pesudovs 2007). On the face of it the design of this device would seem to effectively standardize for all possible variances mentioned previously as glare distance, angle, target luminance and eye illuminance are controlled for. However a number of problems with its design have been highlighted. Firstly the way CS is measured is very unreliable. The patient presses a button if the target is seen and if the button is not pressed the target is missed. This could be very criterion dependent, where a participant may well be biased towards one response over another. Secondly, the screen illuminance doubles when testing under the glare condition as the white interior of the machine reflects the glare light, producing a greater veiling luminance and further reducing the contrast of the target relative to the background. This results in inaccuracies (Pesudovs 2007). Another factor to consider is that the centre of the target for all stimulus sizes is at an equal distance from the glare source. However, as the target size is changed the peripheral parts of the stimulus are at different distances from the glare source affecting the difficulty of the task.

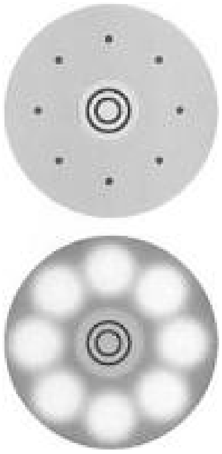

Figure 5.6 showing the target seen in the Takagi CGT-1000 and 2000 (Puell et al. 2006). The glare angle is constant to the centre of the target irrespective of target size. However the glare angle to the outer edge of each target varies as the stimulus size changes (Pesudovs 2007).

Thirdly the repeatability of the test was found to be poor especially for the lowest spatial frequency (largest) and highest spatial frequency (smallest) targets due to the large ceiling effect observed (Pesudovs 2007). An updated version of the device has since been developed (CGT-2000). The updated version appears to incorporate the ability to test binocularly as well as monocularly and at different test distances. Other changes appear to be cosmetic, making the device more user friendly. It is an expensive device to purchase.

Figure 5.7 showing the Takagi CGT-2000 (http://www.takagieurope.com).

The OPTEC 6500 (Stereo Optical Co., Inc. Chicago) see figure 5.8, allows measurement of VA, CS, DG as well as stereo and colour vision. The CS testing is based on the Function Acuity Contrast Test (FACT) (Hitchcock et al. 2004). The FACT system uses sine wave gratings and allows testing of nine CS levels (0.15 log unit steps) at each of the five different spatial frequencies (1.5, 3, 6, 12 and 18cpd). Each CS level is assessed using a 3-AFC method as gratings can be presented vertically or 15° to the left or right of vertical (Bühren et al. 2006). The gratings are presented on circular patches and situated on the display screen in such a way that five patches make up a top row and the remaining 4 patches are situated on a bottom row (Hohberger et al. 2007). CS can be tested at both photopic and mesopic luminance levels, both with and without glare. Glare is produced via 12 LED bulbs situated in an arc around the field incorporating the nine sine wave patches. Results are recorded after the 1st incorrect response (Hohberger et al. 2007).

Problems with the FACT testing method have previously been highlighted. There is a high probability of guessing correctly (33.3%) (Pesudovs et al. 2004). As such the test should incorporate a greater number of response alternatives (McKee et al. 1985). Assessment of device repeatability using correlation coefficients has indicated that testing under the influence of glare at is reduced (Hohberger et al. 2007), to a level not suitable for a decision making process (Vincent 1999; Hopkins 2000).

Figure 5.8 showing the OPTEC 6500. This is a device that can measure a variety of visual functions including CS with and without glare.

The Halometer DG tester (Innovative vision products Inc. Moscow) see figure 5.9, is a device developed first and foremost for assessment of night driving difficulty. It does not appear to be a commercially available device at this time but has been used in the world of research. It consists of an on-axis glare source and a slider mechanism incorporating a movable optotype which can be illuminated with either red or green light. The glare source produces a halo of light seen by the participant (the more intraocular light scatter the bigger the halo) and the optotype is moved towards the glare source until the patient reports it is no longer visible. This is classified as the threshold measurement. Next the optotype is moved away from the glare source until the optotype first becomes visible which is recorded as the true threshold measure of DG. A significant change in glare radius indicates the change in intensity of intraocular light scatter (Babizhayev et al. 2009). The test is carried out at 30cm and measures DG monocularly (Babizhayev et al. 2003). Red targets are reported to show the contribution of wavelength to light scatter and is relative to macular glare sensitivity in accordance with Rayleigh's law (Babizhayev et al. 2003). However Rayleigh scatter is appropriate for only very small particles (less than 1/10$^{th}$ the wavelength of light) (Kerker 1969). Spherical particle of between 1 and 4µm have been reported in the transparent and cataractous human lens which are much larger than 1/10$^{th}$ the wavelength of light (Gilliland et al. 2004). This would indicate that light scatter in the eye is of the Mie variety where light scatter is largely independent of wavelength (Whitaker et al. 1993). Therefore testing with different coloured optotypes would be of little added value. High correlations between the green and red DG scores when using the Halometer have also been observed (Babizhayev et al. 2009). Research using the Halometer has been largely restricted to the developers of the device who have indicated excellent repeatability (Babizhayev 2003; Babizhayev et al. 2003) and good correlations to VA impairment and back scatter measures (Babizhayev et al. 2003).

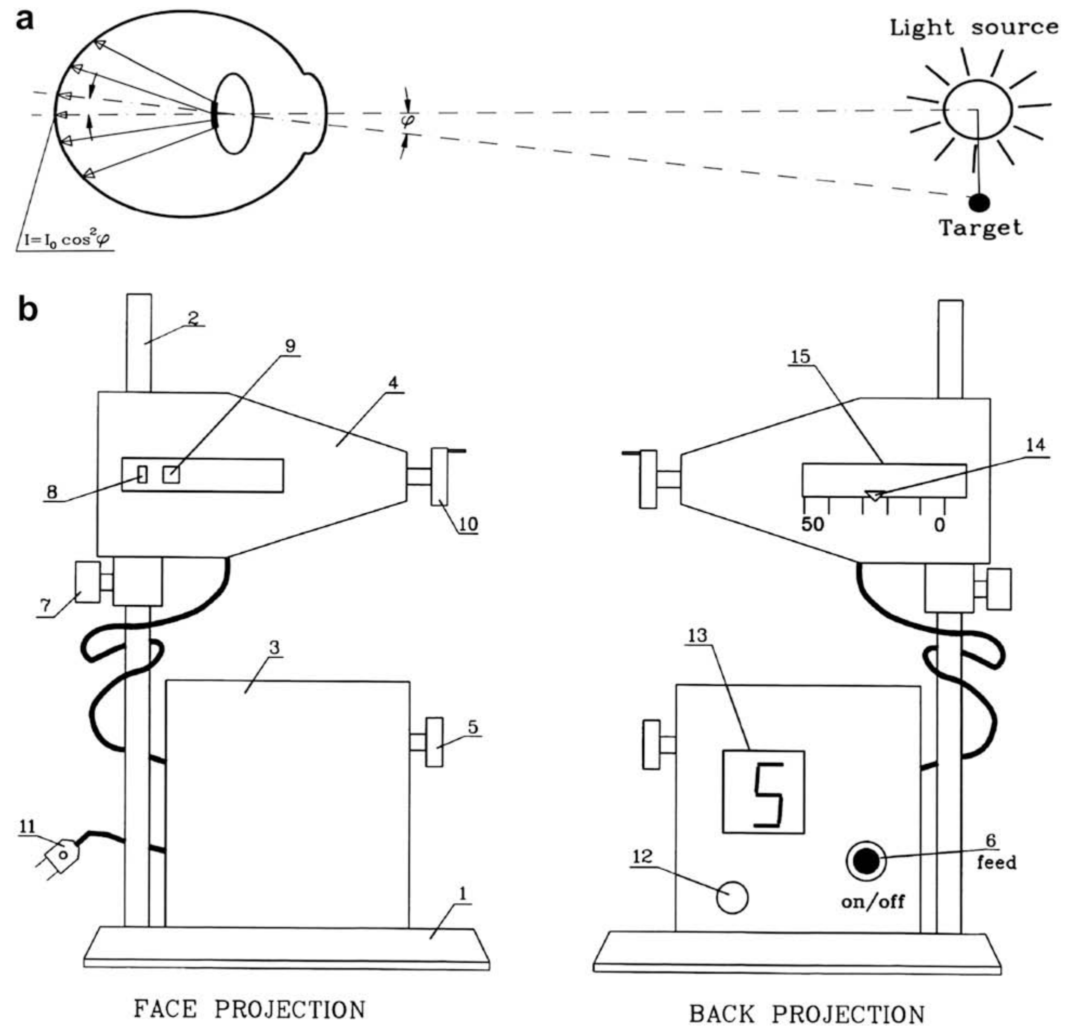


Figure 5.9 showing the Halometer. (a) Principle of the glare test (b) 1) base; 2) support bar; 3) feed source; 4) unit for glare testing as seen by subject; 5) rheostat; 6) on/off button; 7) clamp; 8) glare source; 9) moveable target; 10) mechanism to move the optotypes closer or further from the glare source; 11) plug; 12) a button for choosing among different optotypes, operator side; 13) electronic display of optotype position, operator side; 14) scale showing optotype distance from glare source, operator side; 15) window to show the distance of the optotype from the glare source, operator side (Babizhayev et al. 2009).

The straylight meter (Oculus Optikge-räte, GmbH, Wetzlar, Germany) (van Den Berg 1986; Witmer et al. 1989; Veraart et al. 1992) see figure 5.10, uses a ring-shaped straylight (glare) source which is flashed on and off at a frequency of approximately 8 Hz. This can be presented at varying eccentricities. The subject fixates on a central target. In the ‘on’ phase light will reach the fovea due to light from the straylight source being scattered in the eye, diverting it to the fovea. In the ‘off’ phase no light will be scattered and so the fovea will only receive light from the central fixation target. If the central target is black in both phases a flickering signal will be perceived due to the scattering of light from the straylight source. If some compensation light is added to the central target in the ‘off’ phase, the flicker strength will diminish. The flicker will cease to be apparent if this compensation light is increased to equal the amount of straylight, allowing a precise measure of retinal straylight to be made (van den Berg et al. 2009b). The straylight meter can be used at varying eccentricities, 3°, 10° and 28°. At 28° the test is poor at discriminating between normals and patients with early cataracts and less reliable than other straylight scores (Elliott and Bullimore 1993). As there was high correlation between the 3° and 10° angles and cataract scores, assessment of cataract could be done at either of these angles (Elliott and Bullimore 1993). It was reported that cataract patients found it easier to perceive the re-appearance of the flicker than to judge its disappearance (Elliott and Bullimore, 1993). Franssen et al. (2006) also stated there was no control over the subject’s measurement reliability as the patient was in complete control of the device at all times. This led to the development of an updated device called the C-Quant. This works in a very similar way to the straylight meter. The main difference is the target, which is split into two and the patient is asked which half is flickering more strongly. It is a 2AFC method bringing a greater control over the results obtained (van den Berg et al. 2013). A new computer implemented version of the straylight meter (NSLM) has been developed more recently allowing for binocular straylight measurement (van Rijn et al. 2005).

The straylight meter has been used more frequently than any other device in glare testing research over the last 10 years, although again much of the research has been done by the team responsible for its inception. It has been suggested as the closest thing to a 'gold standard' device currently available for measuring DG (van Rijn et al. 2005) and has been used as a gold standard measure to compare other devices (Elliott and Bullimore 1993; van Rijn et al. 2005). Straylight meter measurements have been shown to be repeatable (Elliott and Bullimore 1993; Cervino et al. 2008; van den Berg et al. 2009b; Guber et al. 2011), show greater discriminative ability between normal patients and cataract patients than other glare tests (van Rijn et al. 2005; van den Berg et al. 2009b), be more strongly related to LOCS scores than VA or CS (Michael et al. 2009) and show good correlations with perceived driving difficulty (van Rijn et al. 2005). However successive measurements have been shown to be related indicating the device could be prone to fraud (van Rijn et al. 2005). A new version of the straylight meter (NSLM) which measures visual function binocularly has been developed but more research needs to be undertaken in order to fully evaluate this device (Aslam et al. 2007). As this is the only version that measures visual function binocularly it would appear to be the most appropriate for any driving assessment.

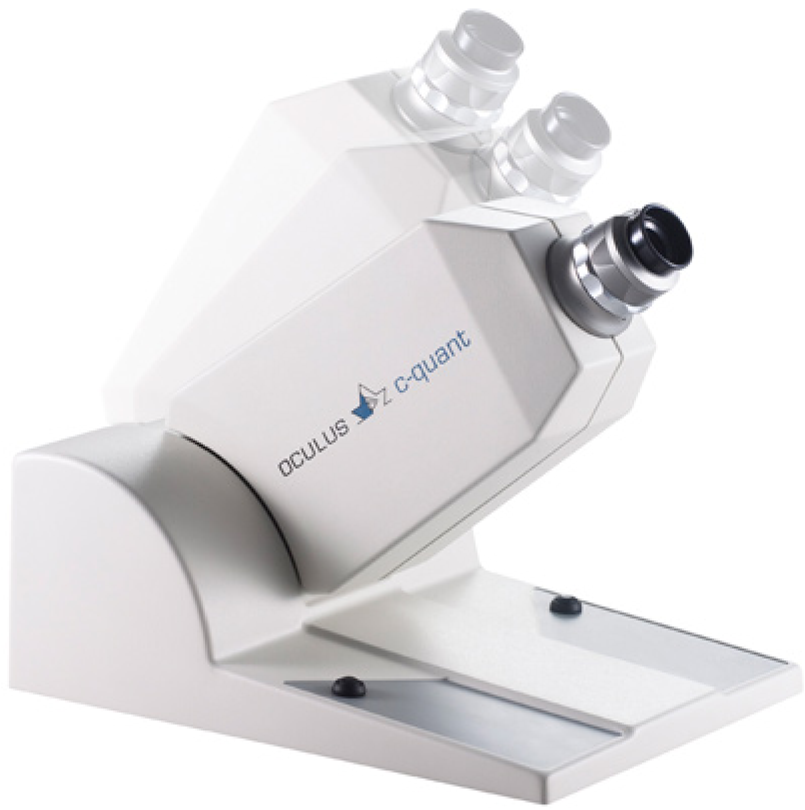


Figure 5.10 showing the C-Quant straylight meter (http://www.oculus.de).

The straylight meter measures a slightly different parameter to CS and DG. It measures directly the relevant physical magnitude affecting the eye (retinal straylight) (van den Berg et al. 2009b) rather than a reduction in visual performance (visibility). This could cause problems as it is difficult for the practitioner and maybe more importantly for the patient to visualise how a result obtained corresponds to real world visual disability. How many letters they have missed on a chart for example is easier to comprehend. Again this is also a costly device to purchase.

The Nyktotest (Rodenstock GmbH, Ottobrun, Germany) and Mesotest (Oculus GmbH, Wetzlar, Germany) see figure 5.11, were both designed in Germany for use in the assessment of driving standards, particularly to assess how CS is affected by glare under low luminance conditions. The Mesotest is recommended by the German Ophthalmological Society for the assessment of night driving, although this has not yet been introduced into normal driving standard assessments. The Mesotest and the Nyktotest use a surround luminance of 0.032 and 0.1cd/$m^2$ respectively, measuring CS at different levels. When glare is added in both instruments the same contrast levels are tested, but at a luminance of 0.5 log units higher (van den Berg et al. 2009b). Although recommended for use since their inception (Aulhorn and Harms 1970; Lachenmayr and Pateras 1987; Grosskopf et al. 1998; Rassow 1999) in Germany for night driving assessment, little has been done to test the repeatability, discriminative ability and validity of these devices (van Rijn et al. 2005). The Nyktotest and Mesotest have been shown to relate well to perceived driving difficulty at night, particularly in those with good VA (van Rijn et al. 2002) but when they are directly compared to the straylight meter, results would indicate poorer performance. Repeatability has been shown to be better for the straylight meter when directly compared to the Nyktotest and Mesotest (van den Berg et al. 2009b) and discriminative ability, validity and additional information over VA measures have all been shown to be superior for the straylight meter (van Rijn et al. 2005; van den Berg et al. 2009b). It should be noted that the studies mentioned above all compare the Mesotest and Nyktotest against the straylight meter, the device developed by the authors, so results should be taken with caution. Little other comparison or evaluation of the Nyktotest or Mesotest appears to exist presently. Again this is an expensive device to purchase.

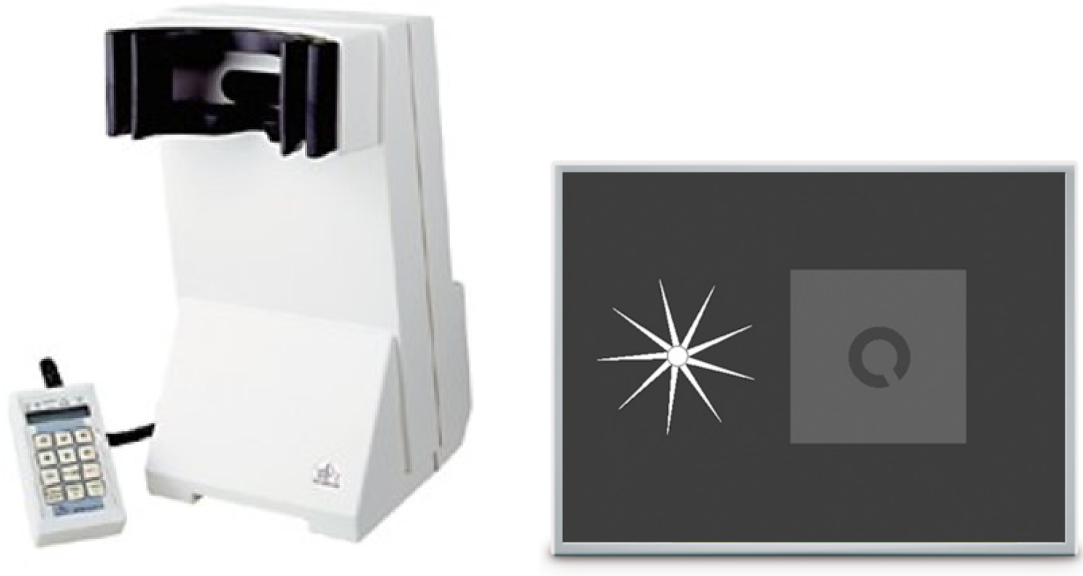

Figure 5.11 showing the Mesotest II and a representation of the task (http://www.oculus.de).

The most recent device developed in this area is the EpiGlare Tester (Epico, LLC, Columbus, OH, USA) see figure 5.12, designed to specifically mimic car headlight glare. It is attached directly to a phoropter system providing point source illumination at constant intensity and spectrum, and with a defined angle of incidence to the eye. The LED light source is controlled to approximate a median level of luminance between high intensity discharge and incandescent tungsten halogen systems at a distance of 40m, miss-aligned by 1.5° at average passenger car mounting height (Epitropoulos et al. 2015). The glare source consists of 4 sources of light positioned around the aperture for viewing in each eye. The internal device is black in colour to minimise internal reflections (Epitropoulos et al. 2015) counteracting the problem with the Takagi CGT 100 previously identified (Pesudovs 2007). VA using a Snellen or logMAR chart, is measured with and without the glare source and the difference between the two measurements is a measure of DG. This can be done both monocularly and binocularly.


Figure 5.12 showing the EpiGlare tester (Terence P. O'Brien, MD).

There is little research published in regard to the effectiveness of this device but early results have reported that subjectively 83% of participants felt the device effectively represented the difficulties experienced when driving at night. In those without cataract, 71% of subjects reported that they were minimally affected by the glare source (Epitropoulos et al. 2015). As would be expected, the reduction in visual performance caused by the glare source was significantly more pronounced in those with cataracts when compared to normal participants (Epitropoulos et al. 2015). There is also no real detail as to what was classified as cataract. Therefore more work clearly needs to be done to fully evaluate this device although certain aspects of its design show promise.

Table 5.1 Overview of studies that have previously evaluated glare testers in chronological order

| Glare test(s) assessed | Study population | Description of assessment | Reference |
|---|---|---|---|
| Vistech MCT 8000, Miller-Nadler, BAT, Berkeley, Straylight meter | 24 young normal patients, 22 old normal and 33 with cataract (VA better than 20/70). | Direct comparison of devices in terms of repeatability, discriminative ability and validity measures in comparison to the straylight meter. | Elliott and Bullimore (1993) |
| Mesotest and Nyktotest | Mesotest: 176 patients, 85 with monofocal IOL, 50 with multifocal IOL and 41 with early cataract. Nyktotest: 50 people divided into 3 age groups. | Mesotest: Elderly pseudophakic patients and those with early cataract could not fulfil the criteria for driving standards due to CS and glare. Nyktotest: Older patients and even some younger patients could not fulfil the requirements for driving standards. | Grosskopf et al. (1998) and Rassow. (1999) |
| Mesotest and Nyktotest | 93 subjects, 50 years and older with at least VA of 20/80. | Correlations with perceived driving difficulty indicate that the Mesotest and Nyktotest scores correlate well with perceived driving difficulty at night. | van Rijn et al. (2002) |
| Halometer | 28 cataract patients. | Good correlations were shown between repeated measures and DG measurement was found to correlate well with measurements of back scattered light. | Babizhayev et al. (2003) |
| Mesotest, Nyktotest, C-Quant SLM, and the NSLM | 112 subjects split into three categories, young, old normals and subjects with early cataract in at least 1 eye. | Repeatability was found to be similar for all tests. Discriminative ability and correlations with perceived glare difficulty were found to be superior for the straylight meters. van den Berg et al. (2009) found the repeatability to be superior for the straylight meter. | van Rijn et al. (2005) and van den Berg et al. (2009b) |
| Optec 6500 | One eye from 61 normal subjects. | The device is prone to guessing and repeatability under mesopic conditions was reduced. DG was found to increase with age. | Hohberger et al. (2007) |

| | | | |
|---|---|---|---|
| Takagi CGT 1000 | 95 eyes from 61 cataract patients and 13 young normal patients. | Poor repeatability was shown and accuracy of results limited due to floor and ceiling effects. Good correlations were found with LOCS III scores. | Pesudovs. (2007) |
| C-Quant SLM | Two studies the first using 1 eye from 20 subjects and the second using 1 eye from 45 healthy subjects. | Repeatability was found to be good for the C-Quant SLM. | Cervino et al. (2008) and Guber et al. (2011) |
| Halometer | 65 older patients with cataract in at least 1 eye and 72 older patients without cataract. | Older drivers were more likely to have increased DG scores, further exaggerated when cataract was present. | Babizhayev et al. (2009) |
| Vision monitor MonCv3 (computerised variant on the Halometer) and the C-Quant SLM | The right eyes of 51 normal subjects with VA of at least 20/25. | A significant correlation was found between halo size and SLM readings. | Puell et al. (2014) |
| EpiGlare | 80 eyes with cataract and 98 eyes without cataractous changes. | Significant differences were shown between the DG experienced by cataractous eyes and normal eyes. | Epitropoulos et al. (2015) |

| Table 5.2 showing the strengths and weaknesses of commercially available glare testers | | | | | | | |
|---|---|---|---|---|---|---|---|
| Glare test | Psychophysical method | Target | Glare source | Cost | Time taken | Portability | Understanding |
| BAT | Descending method of limits, 26-AFC, monocular testing | Letters. | Self-illuminated hemispherical bowl. Glare source always equi-distant to the target | ~£800 | ~2 minutes | Easily portable, small and light. | Easily understood (missed letters). |
| CSV-1000 | Descending method of limits, 2-AFC, monocular or binocular testing. | Sine wave gratings. | 2 peripheral halogen lamps. Central targets further from the glare source | ~£3000 | ~2 minutes | Portable, can be wheeled around. | Easily understood (missed targets). |
| CGT-1000 | Criterion-dependent method. Monocular or binocular testing. | Dual concentric circles | 12 LED's situated in a ring around the target. Glare source always equi-distant to the target | ~£6000 | ~2 minutes | Bulky self-contained unit, 22kg. | Easily understood (missed targets). |
| Optec 6500 | Descending method of limits, 3-AFC, monocular or binocular test. | Sine wave gratings | 12 LED's situated in an oval around target. Central targets further from the glare source. | ~£5000 | ~2 minutes | Reasonably portable self-contained unit. 6-8kg. | Easily understood (missed targets). |
| Halometer | Ascending method of limits, normally 26-AFC, monocular test. | Letters or Landolt rings if needed. | Rheostat controlled glare source. Glare source position not critical | Not known | Dark adaption required, after which ~2 minutes | Bulky | Easily understood (distance from glare source when target becomes visible). |
| CSLM | Method of adjustment. Monocular test. | Luminance level of target. | Annulus around target. Glare source always equi-distant to the target | ~£5000 | ~ 5 minutes | Connected computer reduces portability | Difficult for the patient to comprehend. |
| Nyktotest and Mesotest | Descending method of limits, 6-AFC, monocular or binocular assessment. | Landolt ring. | LED glare source. The part of the Landolt ring missing will vary I distance from the glare source | ~£7000 | ~2 minutes | Connected computer reduces portability. | Easily understood (missed targets). |
| EpiGlare | Descending method of limits, 26-AFC, monocular or binocular assessment. | Letters | 4 LED's positioned around the eye piece. Glare source always equi-distant to the target | ~£1500 | ~2 minutes | Portable, attaches to any phoropter. | Easily understood (missed targets). |

## 5.4 Conclusion

Early glare tests suffered from various design issues, mainly the problem of standardizing light intensity, distance and angle of the glare source from the eye, aspects that have all been shown to be of vital importance (Vos 2003a). Others suffered from the lack of a geometric progression between contrast levels reducing the repeatability of devices (Elliott and Bullimore 1993). More modern designs have attempted to remedy these issues with varying degrees of success but further deficiencies and other aspects, such as cost, repeatability, discriminative ability, portability, time taken and public/practitioner understanding mean a universally accepted ‘gold standard’ has not been found (see table 5.2). Glare tests that are inexpensive, accessible, repeatable, discriminative and valid are needed and further research necessary before any universally applicable test can be found (Aslam et al. 2007).

## 5.5 Questionnaires and their analysis

Questionnaire responses have been used in various studies investigating the link between driving performance /crash rates/ glare results and perceived difficulties. Most examples used are examples of rating scale questionnaires which involve a number of questions with a number of response categories. Each of these response categories usually has a different score assigned to it. This technique is called a Likert scoring scale and the scores for each response category are normally the same for each question or item. This is not valid unless every item elicits exactly the same level of symptom. For example on a depression questionnaire with a 4-point Likert scoring system (0-3) if someone fully endorses the question “I feel suicidal” and also “I laugh less than I used to” both would give the same score when surely one question refers to much more severe symptoms than the other (Mallinson 2007).

Rasch analysis is an item response theory based model that attempts to address this problem (Wright and Linacre 1989; Davey et al. 2013). It uses the responses from all patients for all items in order to rank them in terms of severity, and then also to rank patients according to the severity of symptoms they exhibit. This ranking allows us to find out if the questionnaire elicits an appropriate level of symptom severity.

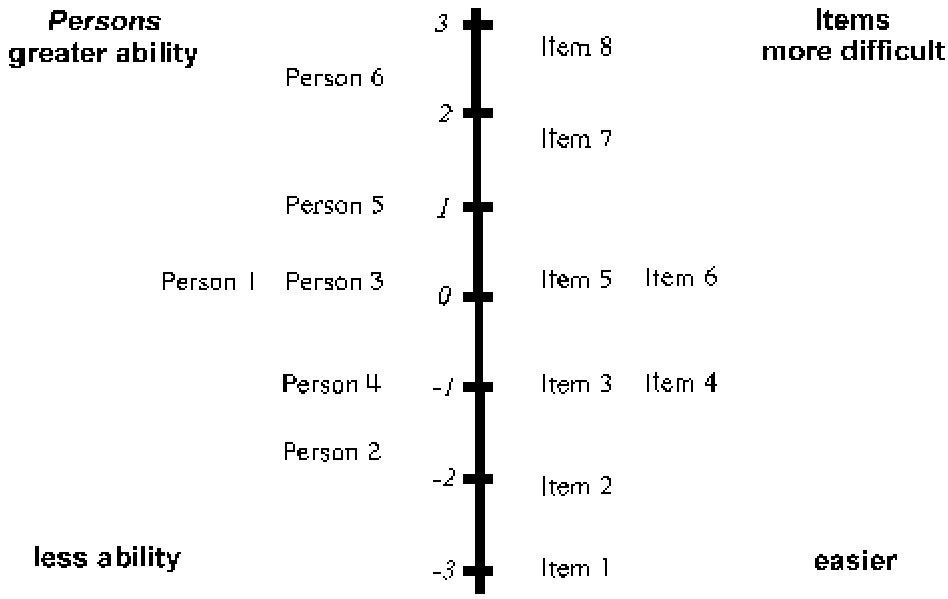


Figure 5.13 showing a simple example of an item map used to assess whether a questionnaire is too difficult or too easy. If all items are towards the top and participants towards the bottom the questionnaire is too difficult or the symptoms measured are too severe. If all the participants are towards the top and all the items are towards the bottom the questionnaire is too easy or the symptoms measured are not severe enough.

All items and participants are ranked on the same scale according to the severity of symptoms or the difficulty of a task, the top of the graph being most severe or most difficult. If all the items are towards the top and the participants toward the bottom this means that the participants have failed to respond that they suffer from any of the symptoms tested and therefore the questions are too severe, known as the floor effect. If things are found to be the other way around, the questions are too easy, known as the ceiling effect (Bond and Fox 2013).

Subsequently this allows mis-fitting items, which do not conform to the model to be identified. For example if there is a question that someone with overall mild symptoms endorse and people with more severe symptoms do not it would be described as a mis-fitting item. With Rasch analysis, mis-fitting items can show a greater than expected variability or predictability in participant responses. If an item becomes too variable this could lead to unreliability or to the measure of a different symptom altogether (Wright et al. 1994). If an item is too predictable, no additional information is generated by that particular item. Mis-fitting items can therefore be removed. Rasch can also be used to examine whether response categories should be merged together or not (Vianya-Estopa et al. 2010). For example in a population with mild symptoms the third and fourth response categories could be combined if the analysis concluded that they offer no improvement in patient separation. In some cases collapsing response categories can improve the discriminative ability of the questionnaire.

Rasch analysis also contains a form of factor analysis called Principle Components Analysis (PCA) which detects whether a scale is multi-dimensional. PCA is used to see if the questions used are measuring the same dimension (symptom). If more than one dimension is found within a scale then the questions for each dimension should be separated and analysed separately (Linacre 1998; Bond and Fox 2013).

## 5.6 Visual Function Questionnaires

Various studies have used visual assessment questionnaires to try and correlate subjective visual problems with objective findings. There are many different options to choose from when deciding which would be prudent to use with a particular study.

McAlinden et al. (2011a) compared 16 regularly used cataract surgery outcome questionnaires via Rasch analysis in order to test performance. During this analysis the Catquest-9SF questionnaire was shown to perform superiorly but did not incorporate any questions about driving difficulty. The next most responsive (ability to detect clinically important differences) was the Visual Disability Assessment questionnaire (VDA) and its three different sub-scales.

Khadka et al. (2013) compared the performance of all available ophthalmic questionnaires. Of the 17 cataract questionnaires examined once again the Catquest-9SF and the VDA were the two which demonstrated superior psychometric properties. The Refrative Status and Vision Profile (RSVP) questionnaire which contains a sub-scale targeted to driving difficulty was also analysed, however this failed to satisfy all the requirements of the Rasch measurement model (Gothwal et al. 2010).

The purpose of using a questionnaire in this study was to assess perceived driving difficulty in participants with varying degrees of media opacity (cataract). In both comparison studies above, the same questionnaires were highlighted as having superior pychometric properties. Only one of these contained any questions about driving difficulty and therefore the VDA distance/lighting/reading sub-scale was chosen for use in this study.

## 5.7 Visual Disability Assessment Questionnaire

Like most questionnaires the VDA (Pesudovs and Coster 1998), was developed using Classical Test Theory and while highly validated this is also a method which has various drawbacks (Embretson and Reise 2000). This approach only gives limited insight into the psychometric properties of the test, and scoring does not provide for interval-level measurement. This scores results as simple sums of ordinal values (1, 2, 3, 4) applied to responses (not at all, a little, quite a bit, and a lot) across all questions (Pesudovs et al. 2010). This scoring system assumes that there are no quantitative differences between each category of response which is not the case making scoring non-linear. “This problem is solved by Rasch analysis, a modern psychometric approach, which transforms ordinal scores into estimates of interval-led measurement” (Pesudovs et al. 2010). Rasch analysis provides better information about the performance of a particular questionnaire.

Pesudovs et al. (2010) concluded that after performing Rasch analysis on the VDA questionnaire that it was multi-dimensional (measuring different symptoms) in its original form. This violates the fundamental requirement for summating a scale (Rasch, 1980). Uni-dimensionality could be restored by separating the mobility scale from the activity limitation scale. The activity limitation scale could be further sub-divided into the distance/lighting/reading and the near and related tasks sub-scales. All three sub-scales (near and related tasks, mobility and distance/lighting/reading) were found to be valid uni-dimensional measures (Pesudovs et al. 2010). Of the three sub-scales the distance/lighting/reading was found to perform optimally and it also incorporates two questions about driving (see Appendices). Therefore this subscale was used in this project.

# 6.0 The contrast sensitivity clock: evaluation of a simple device for measuring contrast sensitivity and glare

## 6.1 Introduction

Driving is known to be a visually demanding task (Owsley and McGwin 2010). In optometric practice clinicians often hear subjective complaints from patients about car headlights and their associated glare effects (Ball et al. 1998). There are two main types of glare. Discomfort glare is caused by a light source which is too intense for an individual at a given time and place leading to annoyance and/or light aversion (Mace et al. 2001; Mainster and Turner 2012). It has also been classified as the distracting effect of a peripheral light source in the field of view (Vos 2003b). Discomfort glare is normally measured subjectively on a numbered scale. DG has much more of a detrimental effect on the quality of vision. As light enters the eye it is scattered by the ocular media. This intraocular scatter produces a veiling luminance, reducing the contrast of the retinal image and making objects harder to see (Vos 1984; Vos 2003a; van den Berg et al. 2013). DG is normally quantified by the reduction in VA or CS caused by a glare source or by the direct measurement of straylight (van Rijn et al. 2005).

Older drivers are the fastest growing group of motorists on the roads and are also driving more often and further than previous generations (National Highway Traffic Safety Administration 1989). Cataract is more prevalent in the older population with around 60% of people 65 or over having some form of moderate cataract (Mitchell et al. 1997). Cataract is well known to substantially impair CS, especially when a glare source is present (Elliott and Bullimore 1993; van Rijn et al. 2005; van den Berg et al. 2009b; Nischler et al. 2010). Subjective reports of difficulty are more common in these individuals (Owsley et al. 1999) and they tend to avoid more challenging conditions such as driving at night, in inclement weather or at rush hour (Ball et al. 1998). Drivers with a history of crash involvement have been found to be 6 times more likely to have a serious CS deficit in both eyes compared to crash free drivers (Owsley et al. 2001). Studies like these have led to calls for VA testing to be supplemented by other types of screening approaches on the driving population (Babizhayev et al. 2009; van den Berg et al. 2009b; Owsley and McGwin 2010).

In 2009 there was an amendment to a European directive (2009/113/EEC, Brussels 2009) which promoted greatly enhanced levels of visual assessment by competent clinicians when assessing driving ability. One of the areas to be given more attention was that of CS and glare. Despite this directive neither of these visual functions is routinely tested as part of the UK's driving standards assessment.

The purpose of this study was to further develop and evaluate the performance of the contrast sensitivity clock (CSC), a simple device for measuring CS and glare. Its ability to successfully distinguish between those with and without cataract was assessed and the potential for its use as a screening device in the driving standards process, discussed.

### *6.1.1 Desired design features*

There have been a number of different devices previously designed to measure CS and DG or equivalent. Some of the more well-known/used devices have been described in chapter 5, however none of these have gone on to become a widely accepted ‘gold standard’ device.

The CSC was developed as a simple test for measuring CS and glare, eliminating some of the previously highlighted issues with glare testers and their use (chapter 5). The clock was designed to be quick and easy to perform, allow for both monocular and binocular testing and in a way that would be easily understood by both patient and practitioner alike. The desired device would be portable and relatively cheap to produce (estimated production costs ~ £300). The contrast steps were required to follow a uniform logarithmic progression using a multiple forced-choice method, as recommended by the American Academy of Ophthalmology (AAO) (Elliott and Bullimore 1993). The device was also designed such that the same light produced both the target and veiling luminance (see section 2.9), meaning the DG produced by the device would always remain constant. This standardisation of test difficulty was one of the main issues with some of the earlier glare testers and in some of those still used today.

Letters were chosen over sine waves as stimuli as they normally offer greater variation for patient response and are therefore less prone to guessing (Hohberger et al. 2007). A CS step size of 0.15 log units was used in the clock design as other devices, including the initial inception of the Pelli-Robson chart (Pelli et al. 1988), the Optec 6500 (Hohberger et al. 2007) and the Takagi CGT 1000 (Pesudovs 2007) use similar step sizes. This step size also fitted in well with the size constraints of the glare device available for production purposes.

The aforementioned size constraints meant that it would not be possible use several trials at each contrast level as recommended by the AAO. The CSC uses only one trial at each contrast level. The quality of the printing used to produce the clock stimuli only allowed accurate reproduction to a CS level of approximately 1.575 log units. Higher CS levels than this were found to be inaccurate and unsuitable for testing. The clock was therefore designed as a screening device and not a method for measuring contrast threshold. Given the clock design, the test could only be designed with 12 steps. Step sizes of 0.05, 0.10, 0.15 gave minimum CS values of 0.98, 0.38 and approximately zero. A step size of 0.15 was chosen to provide the largest range of scores and scores starting from zero.

## 6.2 Methodology

### *6.2.1 The contrast sensitivity clock*

During the initial development of the CSC a number of Jenbrite high intensity light boxes were sourced. These were small and portable, producing a rectangular light, measuring 12cm wide x 10cm high. The luminance these light boxes produced was measured at approximately 30,000cd/m$^2$ by direct photometry (Minolta Chroma Meter CS-100). These were used as the glare source for the CSC.

This light was incorporated into the CSC design to produce both the target and veiling luminance, hence standardising the amount of DG the device produces as shown by the DG equation described in chapter 2. To do this the light would have to be able to shine up through the stimuli and surrounding area alike. For this reason acetate sheets (Niceday transparency, product No. 183442) were used to print the desired stimuli.

### *6.2.2 Letter contrast and Gamma correction*

The letters used in the design of the CSC were first produced on a computer using InDesign software (Adobe InDesign CS6) and digital grey levels. The fundamental issue is that each digital step in software does not correspond with the same physical change in luminance when printed. Computer monitors suffer from the same problem, and a correction factor (gamma correction) has to be introduced to linearize the computer grey level to the final luminance (and hence contrast) produced, either on a cathode ray tube (CRT), or in our case an acetate sheet.

The main problem with printing the acetate sheets for the CSC is that each individual printer requires its own, slightly different levels of gamma correction which will affect the contrast of the letters. To solve this problem a comprehensive selection of differing contrast panels were printed on a separate acetate sheet using a background computer grey level of 95. These were placed on one of the light boxes and while being back illuminated, photometer readings of each separate panel were taken. These were compared to the photometer readings of the background luminance to calculate the contrast of each grey level. It is important that the same printer is used for every acetate sheet produced as the values found will not hold for different printers. In the production of the CSC an HP Laserjet CM4540 was used to print the acetates.

Next a graph was drawn up showing calculated CS against digital grey level and a logarithmic curve was fitted enabling an equation for the curve to be generated (figure 6.1). KaleidaGraph computer software (Synergy Software, US) produces a line of best fit for the data points collected. KaleidaGraph calculates the values of m1, m2 and m3 to best fit the data. M3 indicates the limiting value of the curve to the far right side of the plot, m2 controls the sharpness of the knee point of the curve and m1 controls the vertical position of the entire curve. Using this equation it was possible to calculate the exact computer grey level needed to generate the required CS level after printing (M0). The Chisq value is the sum of the squared error between the original data and the calculated curve fit.

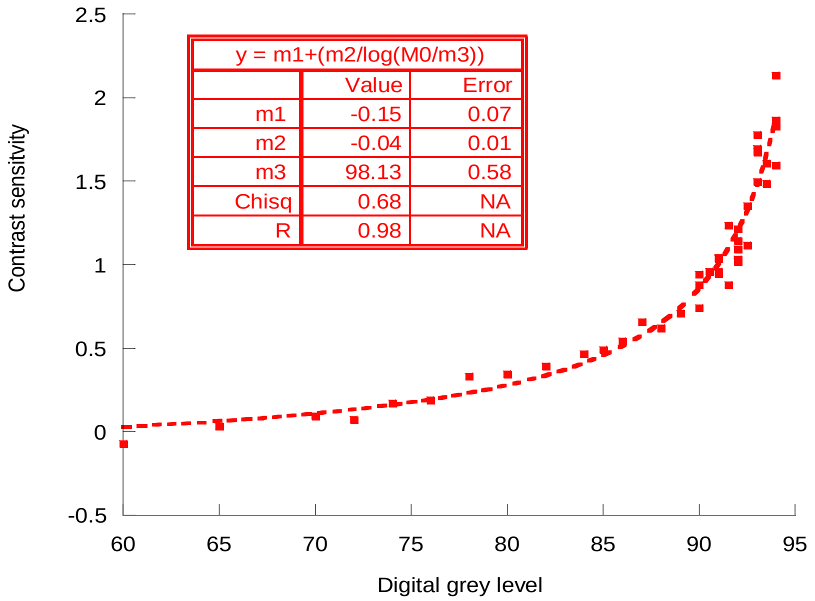


Figure 6.1 showing how computer grey level was calculated from required CS. M0 is the required grey to produce a CS level of y. The values given to m1, m2 and m3 are calculated by the software to best fit the data.

This enabled accurate production of 12 letters, gradually reducing in contrast and positioned as per the hours on a clock face. The position, CS and letter used in each position are shown in table 6.1.

| Clock Time | Actual CS | CS score | Grey level | No glare letters | Glare letters |
|---|---|---|---|---|---|
| 12 | 0 | 0 | 54.32 | Z | S |
| 1 | 0.075 | 0.15 | 66.31 | H | D |
| 2 | 0.225 | 0.30 | 77.65 | S | R |
| 3 | 0.375 | 0.45 | 83.05 | D | N |
| 4 | 0.525 | 0.60 | 86.20 | V | Z |
| 5 | 0.675 | 0.75 | 88.26 | N | N |
| 6 | 0.825 | 0.90 | 89.72 | R | V |
| 7 | 0.975 | 1.05 | 90.80 | H | H |
| 8 | 1.125 | 1.20 | 91.63 | S | K |
| 9 | 1.275 | 1.35 | 92.30 | Z | S |
| 10 | 1.425 | 1.50 | 92.84 | N | Z |
| 11 | 1.575 | 1.65 | 93.29 | R | R |

Table 6.1 above shows the clock time, CS (log units) and grey level required to produce each letter.

The test itself uses Sloan letters of progressively reducing contrast which are printed onto acetate sheets (see figure 6.2). Sloan letters were used as they do not use serifs, they are roughly equal to one another in terms of difficulty and are used on the Pelli-Robson chart (Pelli et al. 1988). They consist of a set of ten letters, C, D, H, K, N, O, R, S, V, and Z. C and O have not been used in this study because of the similarity and confusion between the two at low contrast (Elliott et al. 1990c). This gives an 8 AFC method or a 26 AFC as far as the participant is concerned.

Figure 6.2 shows how the acetate sheets appear:

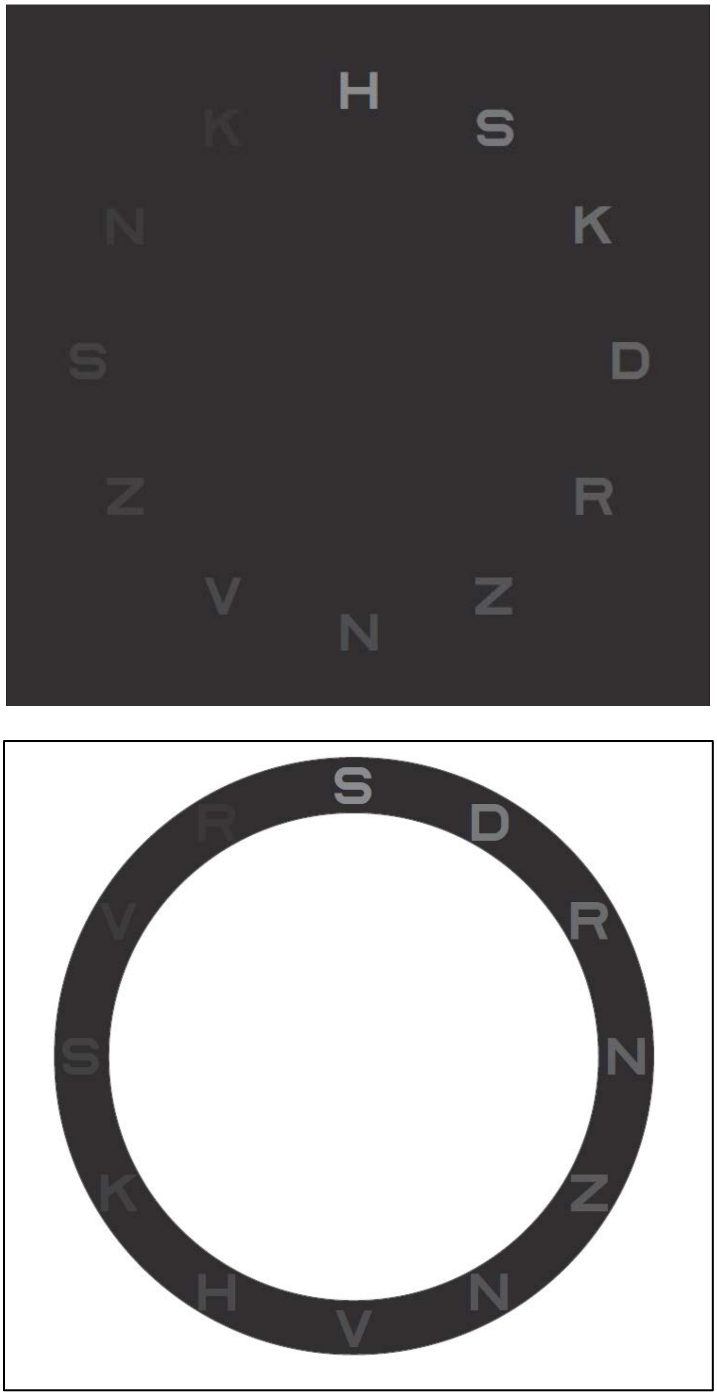


Figure 6.2 showing examples of the acetate sheets giving both the no glare (higher image) and the with glare (lower image) scores. These do not give a true indication of how they appear when used in conjunction with the light box. With the glare sheet the light box provides a rectangular field of the same mean luminance surrounding the letters. There is a 12mm gap above the S at 12 o'clock and below the V at 6 o'clock. At 3 and 9 o'clock the gap to the edge of the light box is 21mm.

Two designs are used shown in figure 6.2 above. The first involves the grey letters being printed onto an even dark background, providing a no glare score. This sheet produces a background luminance of approximately 4000cd/m$^2$, measured via direct photometry (Minolta Chroma Meter CS-100). This background level is much higher than the 85 cd/m$^2$ recommended for optimum measurement of VA using a standard back-lit ETDRS chart. This may have an impact on the CS results generated from the CSC, however Fechner reported contrast threshold to be 1% for a wide range of targets, independent of size and luminance (Fechner 1860). This finding was shown to hold for target sizes between (0.2-3.3cpd) and a luminance range between (~7-514cd/m$^2$) (Zhang and Pelli 1989). The second sheet has the letters printed on a largely clear piece of acetate which gives the glare score for the individual. This sheet exposes the participant to the full luminance of the light box. The participant reads these letters round in a clockwise direction starting from the 12 o'clock position on both sheets and the difference between these two scores (if there is any) gives a score of a person's DG. The test takes a short while to perform, in most cases around 1 minute.

Contrast for letter stimuli, as discussed in chapter two, is best specified using Weber contrast (Pelli and Bex 2013). This can be calculated using the expression ${}^{\Delta L}/_{L}$ where ΔL is the difference in luminance level between the stimulus and background and L is the background luminance. CS is the inverse of the contrast and is normally recorded in log units. Therefore if we imagine a Pelli-Robson chart with an even background luminance of 100cd/m$^2$ and a letter with a luminance of 97cd/m$^2$ then contrast can be calculated as follows.

$$100 - {}^{97}/_{100} = 0.03$$

This can then be changed to CS,

$$CS = log\left({}^{1}/_{0.03}\right) = 1.52\, log\, units$$

The letter at the one o'clock position on the CSC corresponds to a CS score of 0.15 log units and the letter at 11 o'clock corresponds to a CS score of 1.65 log units. Although this is the value each letter scores they have actually been designed to represent slightly different values of CS. The letter in the one o'clock position actually has a CS of 0.075 log units, the one at two o'clock 0.225 log units and so on. The idea behind this was that if a person sees the letter at eight o'clock but fails to identify the one at nine o'clock; they have a better CS than 1.125 log units but worse than 1.275 log units. Their contrast threshold is unlikely to be exactly 1.125 log units, probably more likely somewhere between the two. They are therefore assigned a CS score of 1.20 log units.

The aforementioned acetate sheets are fixed to the light box in such a way that each can be presented separately, allowing a CS reading to be taken with and without glare. The acetates are positioned on the box so that the light shines up through each sheet from beneath. Therefore when using the no glare sheet the black background protects the patient from the vast majority of the glare source and when using the second, clear acetate sheet, the patient is exposed to the full luminance of the box apart from the region against which the letters are presented. Measurements are carried out at a normal reading distance of 33cm.

The letters making up the clock are 4.5mm square. This size of letter fitted well with the size constraints of the light box. Using simple trigonometry each letter on the CSC corresponds to a spatial frequency of approximately 3cpd. This corresponds to a Snellen VA of approximately 6/60, a level which should be easily identified by most people with cataract and especially the driving population and therefore results should be free from acuity limitations. The size of letter used corresponds to approximate peak CS (Campbell and Green 1965b) and is the same spatial frequency target as used by the Pelli-Robson chart at 3m (Mäntyjärvi and Laitinen 2001).

### *6.2.3 Testing Procedure*

148 participants were initially recruited from Stephen Taylor Opticians, Longridge, UK. Participants were chosen from the waiting room of the Opticians practice and were therefore a convenience sample. Ethical approval was obtained from the University of Bradford ethics committee and the study followed the tenets of the Declaration of Helsinki. Subjects were between the ages of 18 and 96 and all had a Snellen VA of 6/15 or better, binocularly. This was to try to replicate the driving population. For ethical reasons those under the age of 18 were not allowed to take part. Participants were required to sign a consent form prior to taking part in the study (see appendices).

Each subject was assessed using the following procedure with habitual correction in place. Contact lenses were included as a habitual correction if the participant attended wearing lenses. Cataract classification was always recorded before the performance with the CS clock was examined. The CS results were noted after an incorrect response to two consecutive letters and participants were also asked to guess if unsure. This order of proceedings possibly left less scope for any bias than if clock scores had been recorded before LOCS III classification took place. This is because LOCS III classification was decided by the practitioner whereas CSC scores were largely a subjective measure:

1) Distance VA was measured with habitual correction in place via a mobile Bailey-Lovie testing chart, calibrated for use at a distance of 3m under bright testing room illumination. This gave a mean chart luminance of 90 cd/$m^2$ measured by direct photometry. This type of chart uses 10 non-serif letters, adopted by the British Standards Institution in 1968. This type of chart shows 5 letters on each line, spaced by a distance equal to one letter width. Each row of letters is spaced by a distance equal to the height of the letters on the better acuity row (Bailey and Lovie 1976). Every letter correctly identified was given a score of 0.02 logMAR meaning each full line equated to a score of 0.1. Measurement ceased when a participant failed to correctly identify more than 3 letters on a line, a method previously shown to give accurate results (Carkeet 2001). The chart included a correction scale for measuring VA at different distances. At a working distance of 3m, 0.30 logMAR was added to the 6m logMAR score achieved.

2) Ophthalmoscopy and slit lamp assessments were performed on every participant. Cataract classification was made via the Lens Opacities Classification System III (LOCS III) grading scale (Chylack et al. 1993b). This classification was carried out via the use of the slit lamp and was performed with the participant un-dilated. Ophthalmoscopy was used to examine the

posterior pole and to examine slightly further into the lens periphery in an attempt to look for any early cortical changes that may otherwise have been hidden by the iris. The LOCS III reference sheet for cataract grading was illuminated via the light box used for CS assessment.

During the design phase of the study, when cataract classification was considered, there did not seem to be any standard way of classifying what constitutes a cataract in previous literature. Previous studies all seemed to use different measures for cataract classification in their research (Elliott and Situ 1998; Stifter et al. 2004; van den Berg et al. 2007; Michael et al. 2009; Nischler et al. 2010; Bal et al. 2011; Shandiz et al. 2011; Sundaresan et al. 2012). Cortical and nuclear opacities with a dilated LOCS score of $< 2$ were previously shown to have a minimal effect on Pelli-Robson CS and DG, whereas posterior sub-capsular cataract at lower LOCS levels were shown to have a more dramatic effect on vision (Lasa et al. 1992).

Cataracts were graded on the extent of nuclear opalescence (NO: 0.1-6.9), nuclear colour (NC: 0.1-6.9), cortical (C: 0.1-5.9) and posterior sub-capsular cataract (P: 0.1-5.9) present. Each subject was classified as having cataract if they had a nuclear grade (NO or NC $> 2$), cortical grade (C $> 1$) and any posterior sub-capsular grade (P $> 0$) in the least affected eye. The LOCS III cataract classification system was not applied precisely because it was not possible for practical reasons to dilate the eyes. The relatively large-scale sample size required meant attending an external practice to recruit participants. It was therefore not viable to dilate patients, many of whom were attending for a routine eye test. This may have resulted in an underestimation of LOCS III scores, especially in cortical opacities. For this reason, in this study, cortical opacities were classified as being relevant cataract at a LOCS score of C > 1, in an attempt to minimise the effect of grading cataract un-dilated. This led to the use of three groups of participants, subjects with clear media, those with bilateral cataract and pseudophakes. Those with cataract in one eye only were classified by the condition of the fellow eye. All results were recorded by one registered Optometrist (CL).

3) An iris colour classification (Seddon et al. 1990). This involves an iris colour scale from 1-5 using four photographs. Grade one indicates an iris with less pigment than in photograph A. Grade two was assigned to any iris which has more pigment than photograph A, but less than in photograph B, and so on (see figure 6.3).

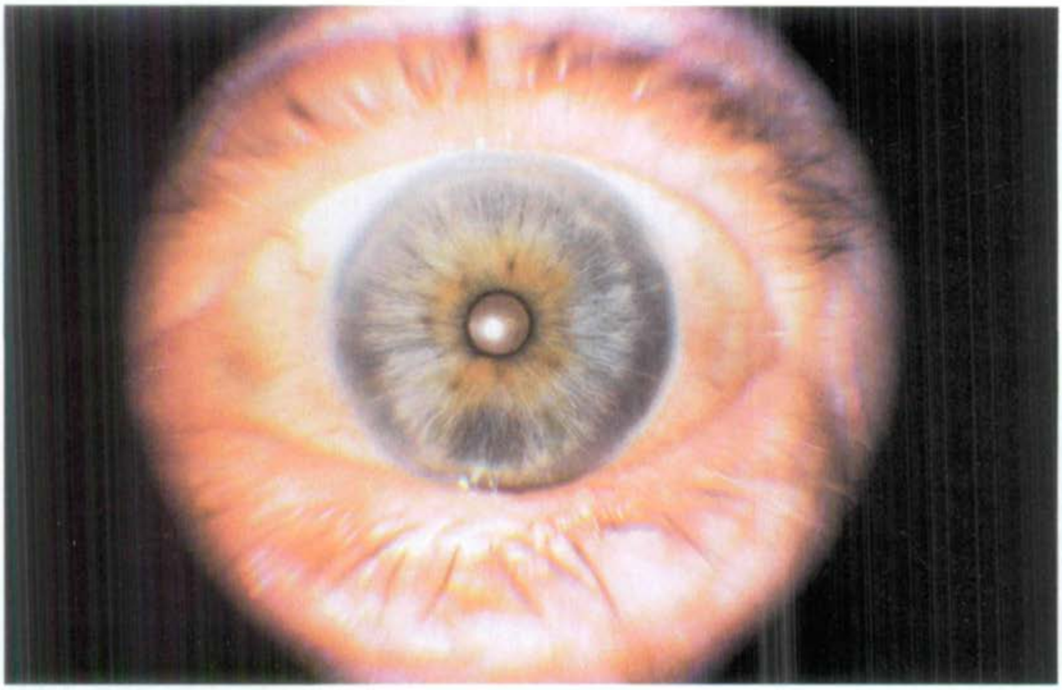

**Fig. 1.** Standard A.

Fig. 2. Standard B.

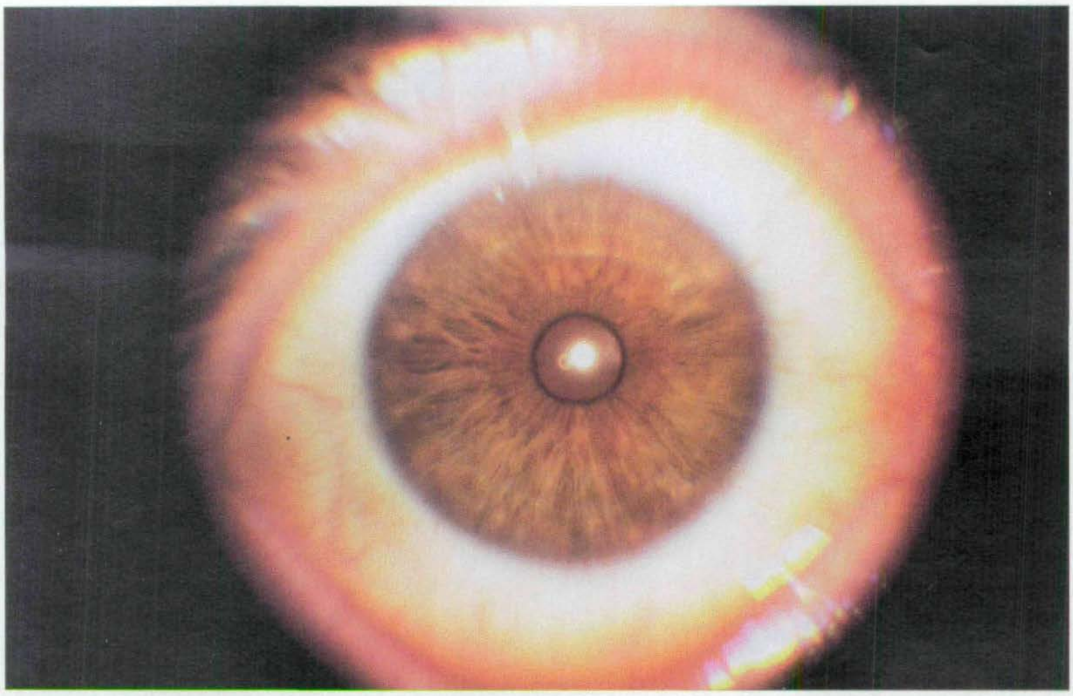

Fig. 3. Standard C.

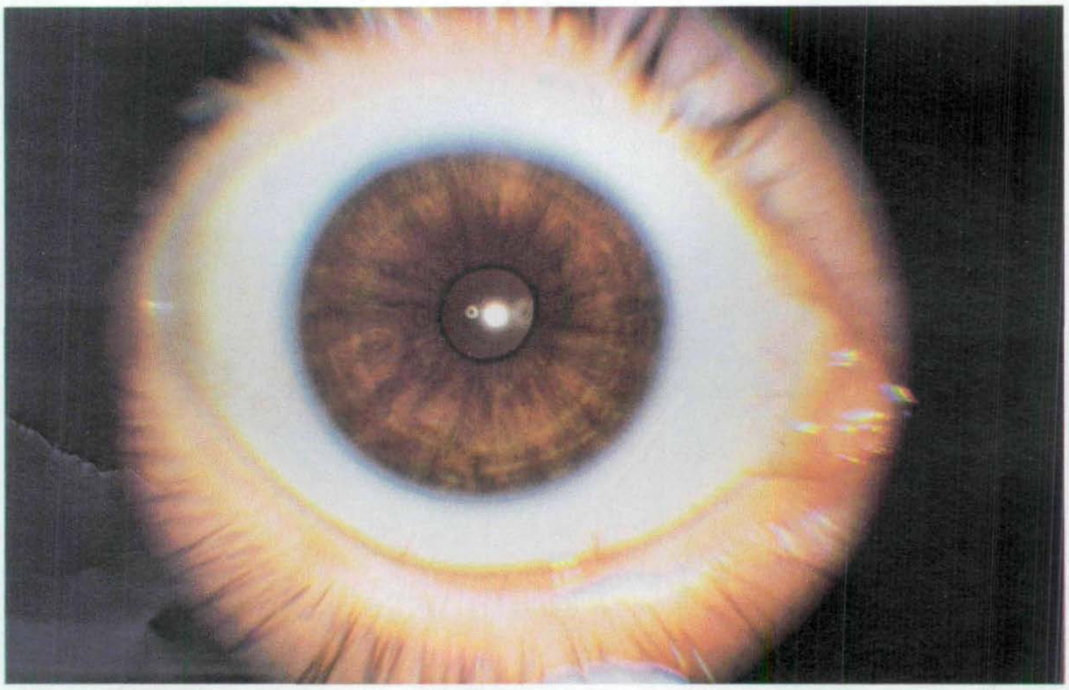

Fig. 4. Standard D.

Figure 6.3 showing the photographs used for iris colour classification purposes (Seddon et al. 1990).

4) The following information was obtained during a short case history; Date of birth, general health, current ocular health and ocular history.

5) The visual disability assessment questionnaire (VDA) was used, specifically the distance/lighting/reading subscale in order to record perceived visual disability in the participants (see Appendices). The sub-scale was shown to be a valid, unidimensional instrument for use with 613 cataract patients awaiting surgery (Pesudovs et al. 2010). Participants were allowed to consider the questionnaire themselves and if any confusion arose, an explanation of what was being asked was given. Both the case history and the questionnaire were carried out at this time in the assessment to give the participant plenty of time to recover from any afterimages that may have been caused by ophthalmoscopy or slit lamp examination (Wu et al. 1990; Mantyjarvi and Tuppurainen 1999).

6) CS was measured binocularly, with and without the glare source, using the CSC. This allowed CS without the glare source (CSCNG), CS with the glare source (CSCG) and DG scores (CSCDG) to be recorded for every participant.

Participants were asked to read the letters with their habitual reading correction in place. Firstly in the no-glare condition and then secondly in the glare condition. The spectacles were examined for any noticeable dirt or scratches, if dirty the spectacles were cleaned and if badly scratched that participant was not used. At contrast threshold participants were given approximately 15-20 seconds to look at the letter and then encouraged to guess (Elliott et al. 1990b). As there is only one letter at each CS level, measurement ceased when the participant volunteered two successive incorrect letters. This was to further reinforce that the correct end point was recorded and to rule out the participant making a careless mistake. Room illumination was not an issue as the intensity of the light box was much greater than any room lighting.

The subjects used during this study were also classified solely by age, either falling into the young or the old group of participants. Other similar studies have found differences in the amount of DG or straylight between younger and older people (Elliott and Bullimore 1993; van Rijn et al. 2005). Once again, as was the case with cataract classification, there does not appear to be a standard age at which people split young and old groups with different studies using different criteria (Elliott and Bullimore 1993; van Rijn et al. 2005; Babizhayev et al. 2009). For the purposes of this study 60 years of age was used as a cut off between groups (young group 18-59 years, old group 60+ years). This level was chosen as it is about the time when cataractous changes start becoming more prevalent (~ 40% of the population at 60 years of age). Before this substantial amounts of cataract are relatively rare (~ 20% of the population) (Mitchell et al. 1997).

### *6.2.4 Amendments to the CS clock*

Initial testing took place on 148 participants and despite CSC results showing significant differences in DG scores between the young/old groups ($Z = -2.56$, $p = 0.01$) and cataract/no cataract groups ($Z = -4.47$, $p < 0.001$) it was clear that a couple of the design features needed to be amended. Firstly, the vast majority of participants were failing to reach the 11 o'clock (CSC score of 1.65 log units) letter on either sheet of the CS clock (figure 6.4). It has been previously shown that CS measures from different tests are not necessarily interchangeable (Bühren et al. 2006) but the actual CS value of 1.575 log units that the 11 o'clock letter represents should be possible to read by the vast majority of participants in the no glare condition at 3cpd (Mäntyjärvi and Laitinen 2001). Secondly the amount of DG the clock exhibited in people was negligible (figure 6.5). Most young normal participants showed no reduction in CS when exposed to the glare source and even some of the cataract patients were showing minimal effects.

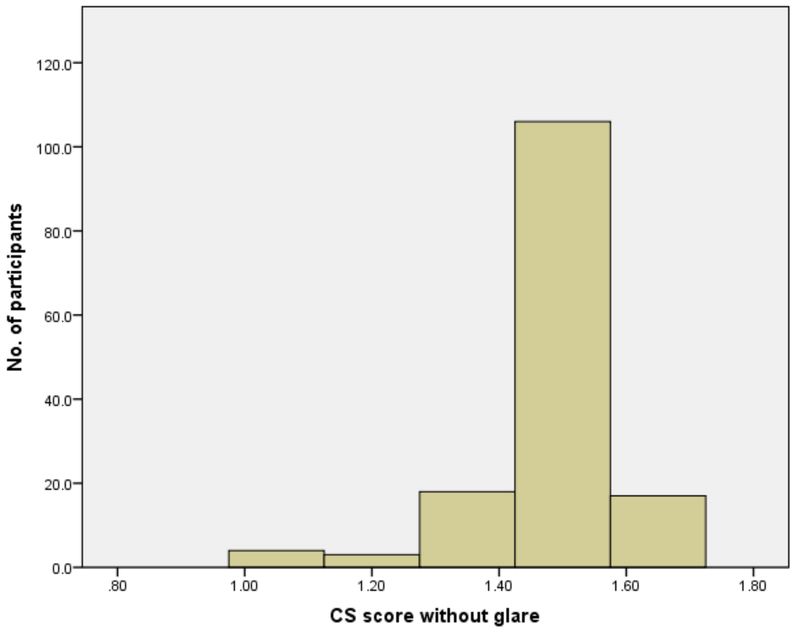


Figure 6.4 showing the number of participants reaching each CS level without glare.

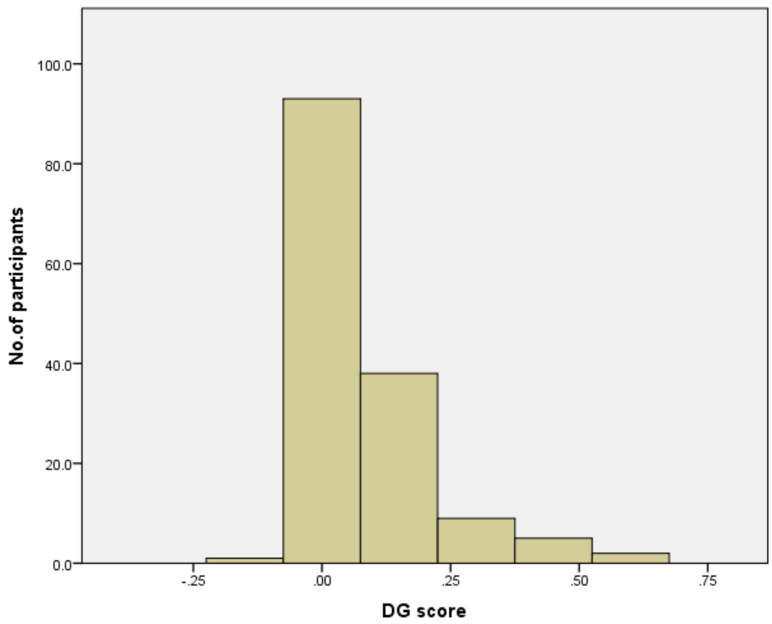


Figure 6.5 showing the amount of DG participants experienced from the initial design of the CS clock.

It was therefore decided to attempt to make some minor amendments to the design of the clock itself. Firstly the accuracy of the printing at the high CS levels was examined. As previously mentioned the design of the CSC involved the 11 o'clock letter having a CS value of 1.65 log units a) because it was designed as a screening device but also b) because the printing at higher CS levels was becoming too variable. In order to improve this accuracy the background luminance of the clock was increased to a grey level of 92, giving slightly more control at the lowest contrasts. The device was then calibrated as previously described. An improvement to the accuracy of the curve fit was produced by dividing the data into two regions: - a high contrast region fitted with a linear function (Fig 6.6) and a low contrast region fitted with the gamma function as previous (Fig 6.7). Using these respective functions it was possible to calculate the exact computer grey level needed to generate the required contrast after printing (see table 6.2).

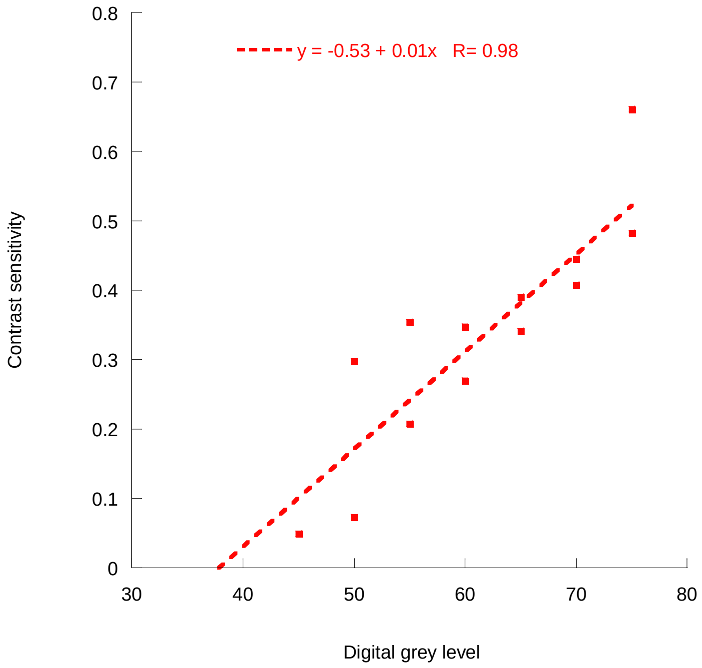


Figure 6.6 showing how computer grey level was calculated from required CS. In the equation x is grey level.

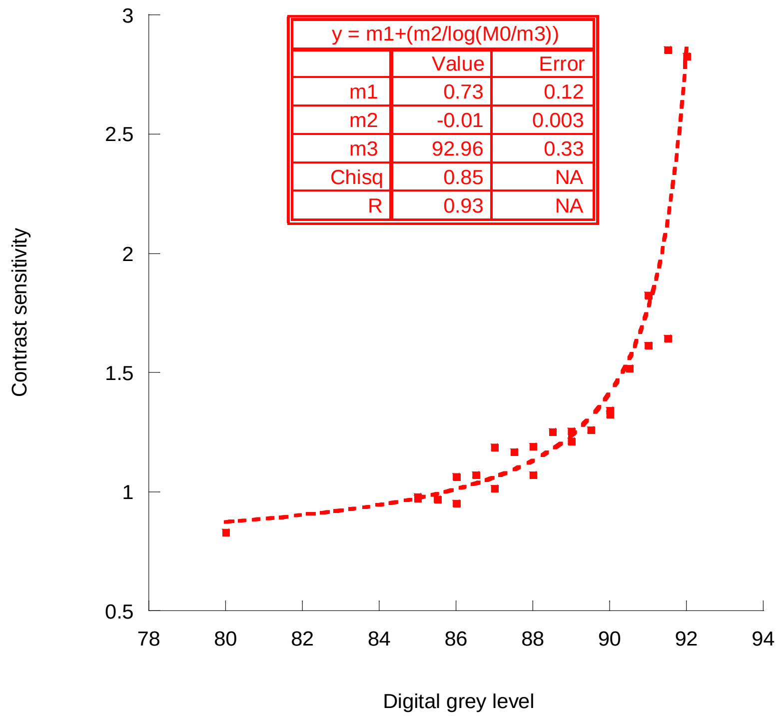


Figure 6.7 showing how computer grey level was calculated from required CS. M0 is grey level.

| Clock Time | Actual CS | CS score | Grey level | No glare letters | Glare letters |
|---|---|---|---|---|---|
| 12 | 0 | 0 | 37.77 | H | S |
| 1 | 0.075 | 0.15 | 56.66 | S | D |
| 2 | 0.225 | 0.30 | 65.88 | K | R |
| 3 | 0.375 | 0.45 | 73.93 | D | N |
| 4 | 0.525 | 0.60 | 78.88 | R | Z |
| 5 | 0.675 | 0.75 | 82.21 | Z | N |
| 6 | 0.825 | 0.90 | 84.60 | N | V |
| 7 | 0.975 | 1.05 | 86.39 | V | H |
| 8 | 1.125 | 1.20 | 87.79 | Z | K |
| 9 | 1.275 | 1.35 | 88.91 | S | S |
| 10 | 1.425 | 1.50 | 89.83 | N | Z |
| 11 | 1.575 | 1.65 | 90.60 | K | R |

Table 6.2 above shows the clock time, CS (log units) and grey level required to produce each letter. A background grey level of 92 was used.

In order to produce a larger DG effect from the device, the ratio between the veiling luminance $L_v$ and the target luminance $L_s$ needed to be exaggerated. As the device was designed at the time there seemed little scope to increase the amount of veiling luminance from the light box and so the target luminance was reduced. This was achieved via the use of a 0.9 log unit neutral density filter to lower the target luminance and background luminance in both the no glare and glare conditions. This was affixed to the acetate sheet with the use of a thin coating of spray mount glue. In the glare condition the filter was only used to back the dial (annulus) shown in figure 6.2, leaving the $L_v$ unaffected and therefore increasing the DG produced by the clock.

After these changes were implemented, 361 people were tested with the updated CSC 2 using the same methods as described above.

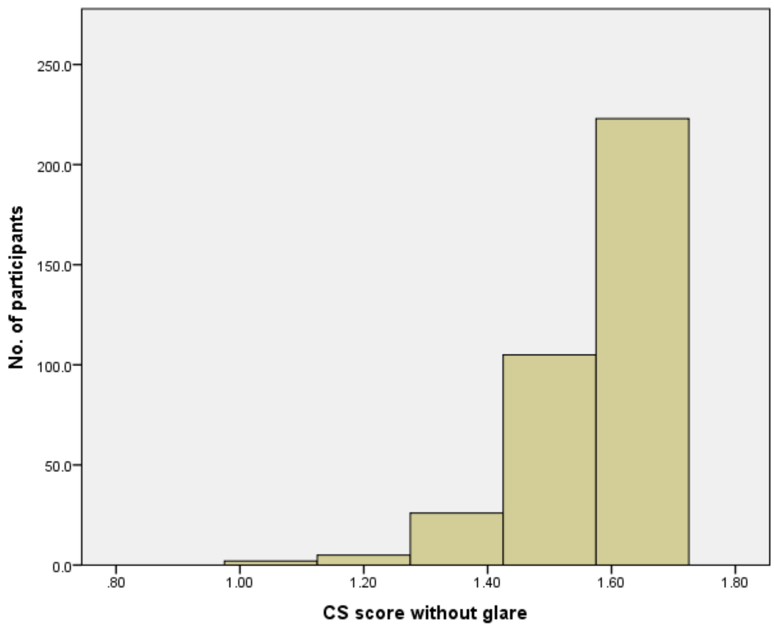


Figure 6.8 showing the number of participants reaching each CS level without glare after the CS clock changes.

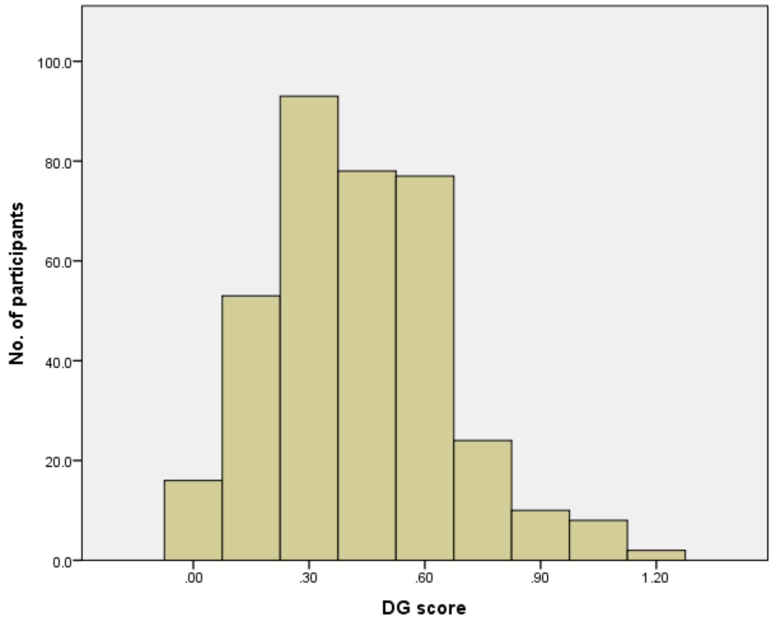


Figure 6.9 showing the amount of DG participants experienced from the updated design of the CS clock.

The changes seemed to produce the desired effect as the majority of people were now able to read the 11 o'clock letter without glare as would be expected (figure 6.8). In the earlier design of the CSC, before the changes implemented, additional background noise likely restricted CS scores. Printing is not a perfectly even process and therefore there is a level of noise when reproducing contrast levels. CS has been shown to be reduced in the presence of noise (Kersten 1984; Pardhan et al. 1993; Rovamo et al. 1993). Secondly the amount of DG experienced by participants was on the whole greater with more variation between different groups of participants with the new CSC 2 design (figure 6.9).

The design of the CSC involved the use of a very bright light source and as such the acetates were tested for fading throughout their usage. It was not possible to use direct photometer readings of the letters themselves as they incorporate too small an area to get a reading with the photometer. Therefore one of the panels used in the calibration of the clock was tested. This panel was attached centrally to one of the light boxes and exposed to the intensity of light for 1 minute bursts (approximately the amount of time it would take to complete the test by one person). After every 50 of these minute bursts, direct photometer readings were taken and the CS level of the panel calculated. This was done for 400 minutes (400 participants) and after this time no change to the CS level of the panel used was observed (table 6.3). The clock itself, when used for testing purposes, was transported carefully in a sealed plastic bag. There was no need to touch the device by participant or examiner during the testing procedure.

Table 6.3 showing the CS of the panel chosen to test for fading (grey level 75 with a background grey level of 92), after each 50 minutes of exposure. There is no difference in the CS of the panel after 400 minutes of exposure.

| Minutes exposed | Max Luminance ($cd/m^2$) | Min Luminance ($cd/m^2$) | Background Luminance ($cd/m^2$) | CS of panel (log units) |
|---|---|---|---|---|
| 0 mins | 1060 | 797 | 797 | 0.50 |
| 50 mins | 1130 | 845 | 845 | 0.47 |
| 100 mins | 1120 | 854 | 854 | 0.50 |
| 150 mins | 1010 | 775 | 775 | 0.52 |
| 200 mins | 1080 | 824 | 824 | 0.50 |
| 250 mins | 947 | 733 | 733 | 0.53 |
| 300 mins | 1040 | 795 | 795 | 0.51 |
| 350 mins | 1000 | 772 | 772 | 0.53 |
| 400 mins | 1140 | 866 | 866 | 0.50 |

### *6.2.5 Rasch analysis*

Rasch analysis (Rasch 1980; Bond and Fox 2013) was used to investigate the VDA questionnaire responses by way of the Winsteps computer software (version 3.91.0), using an Andrich rating scale model (Andrich 1978). Rasch analysis allows different items on a questionnaire to be weighted in terms of difficulty (Latham 2013). Results are recorded in logits (log of the odds ratio) which can be calculated from the expression log $P/_{1-P}$ where P is the probability of someone choosing a specific response for a question (Vianya-Estopa et al. 2010).

The first step of the analysis was to examine the response categories. These should be hierarchical i.e. the response to an item of ‘a little difficulty’ should respond to a higher level of person ability than a response of ‘quite a bit of difficulty’. If this is not the case response categories need to be combined to repair performance (Pesudovs et al. 2010). Rasch analysis also provides summary statistics in terms of person separation which represents how well the questionnaire distinguishes between statistically different levels of participant ability (Pesudovs et al. 2010). Values of person separation of > 2 are generally considered acceptable to successfully distinguish between people of different abilities (Pesudovs et al. 2010; Vianya-Estopa et al. 2010; Tabrett and Latham 2011).

The questionnaire responses were next tested for uni-dimensionality, achieved when only one construct is present in the measurement score. Infit and outfit mean square statistics were used to look for mis-fitting items. The mean square statistics are sensitive to unexpected behaviour affecting responses close to the participant's ability (Bond and Fox 2013), representing the observed variance divided by the expected variance (Pesudovs et al. 2010). Optimum mean square values are found around 1.0 logits. Mean square values between 0.7 and 1.3 logits (30% more or less variance than expected) have been considered acceptable for Likert/survey data (Bond and Fox 2013).

Fit statistics alone are not considered sufficient to examine for different dimensions. A principal component analysis (PCA) of the residuals (observed minus expected scores) was also performed as confirmation of uni-dimensionality (Pesudovs et al. 2010). PCA analysis is used in an attempt to falsify the hypothesis that the residuals are down to random noise by finding the factor or component that explains the greatest amount of variance in these residuals. This factor or component is otherwise known as the 1$^{st}$ contrast in PCA analysis. If the eigenvalue for the 1$^{st}$ contrast is $< 2$ then the 1$^{st}$ contrast is at noise level and therefore the original hypothesis is not falsified. If the 1$^{st}$ contrast eigenvalue is $> 2$ then it is generally considered that there are contrasting patterns in the residuals and an additional dimension/s may be present (Pesudovs et al. 2010; Vianya-Estopa et al. 2010; Tabrett and Latham 2011; Bond and Fox 2013; Davey et al. 2013).

The suitability of the questionnaire for the participant group was examined by way of targeting. If the questionnaire is well targeted to the sample, patient ability will be well matched to item difficulty. Ideally a questionnaire will incorporate both easy and difficult items, with both the item and person mean values in close proximity to each other (Pesudovs et al. 2010).

Ideally the item difficulty of a questionnaire should be the same across different groups of participant. Differential item functioning (DIF) is the term used if there are differences in item difficulty between different groups (Holland and Wainer 2012). In the current study DIF was evaluated for age (young and old groups) and for the presence of cataract (cataract vs no cataract groups). DIF was defined as of no importance for an item if a value of < 0.5 logits was seen between groups, minimal importance if a value between 0.5-1.0 logits was observed and > 1.0 logits considered as meaningful DIF (Lundstrom and Pesudovs 2009; Pesudovs et al. 2010).

## 6.3 Results

Of the 509 people who were tested with the CSC, 148 were assessed with the original design (CSC 1) and 361 with the amended design (CSC 2). Initial testing highlighted some issues with the design of CSC 1 leading to the amended CSC 2 design. The results discussed here will therefore be focussed on the CSC 2.

Results were recorded on adult participants between the ages of 18-96 giving a wide sample of the UK driving population. All statistical analysis was carried out using SPSS Statistics version 21 (IBM Corp. New York).

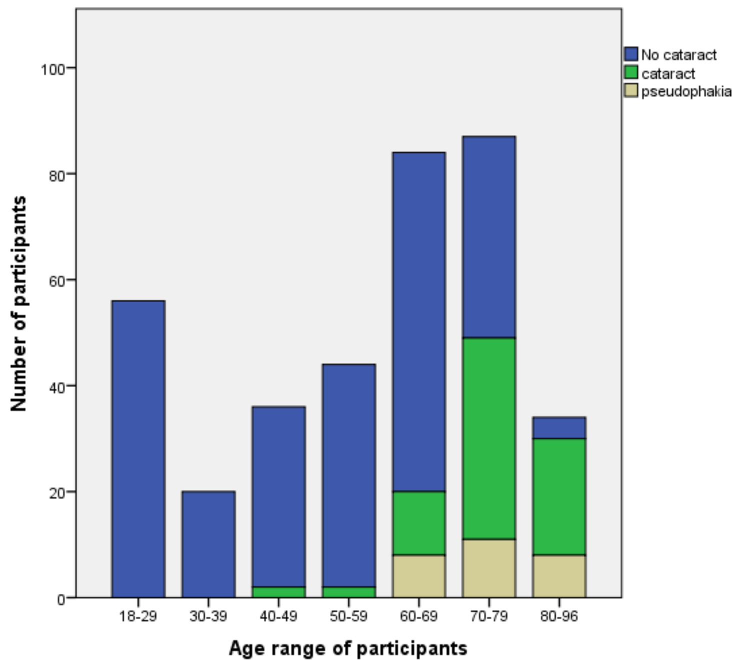


Figure 6.10 showing the age range of participants with with CSC. The number of participants in each age range to have cataract or pseudophakia are also indicated.

Results were taken on a wide age range of participants. Older people are more likely to be affected by a glare source than younger participants and this is exaggerated when cataract is present (van den Berg et al. 2009b). Other than congenital opacities, the earliest cataractous changes can start to appear around 40 years of age, with prevalence increasing sharply in subsequent decades (The Eye Diseases Prevalence Research 2004). Figure 6.10 agrees well with this notion. There is reported to be a doubling in cataract surgery rates for every decade from 40 years of age (Klein et al. 1992). Having the majority of participants in the older age ranges would help to show the relationship between CS and glare in those who are likely to be the most affected. In this data set 30 students were tested from the Optometry student cohorts, who were all in this younger age bracket. This was done in an attempt to introduce some greater variation in iris colour. The practice in Longridge, where the data was recorded, had a patient base where the vast majority of people had light coloured irides.

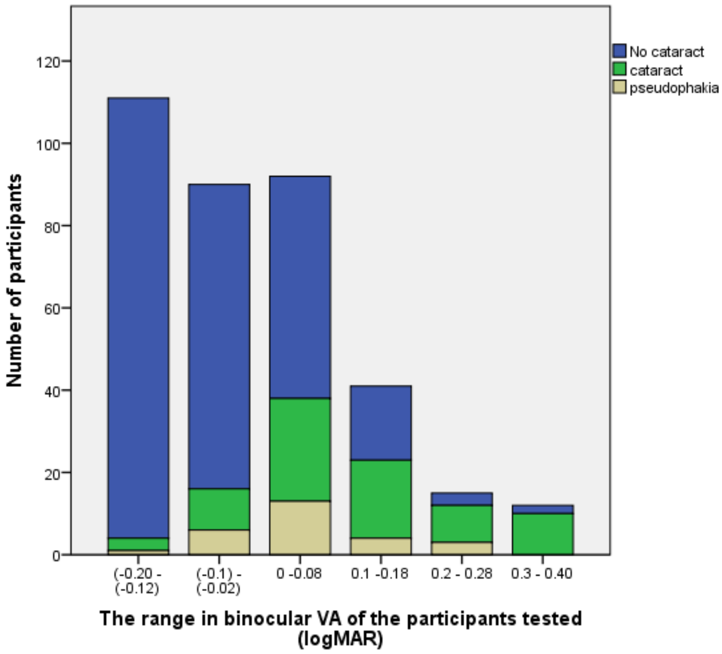


Figure 6.11 showing the range in VA of the participants tested with CSC. Those with cataract and pseudophakia in the relevant VA ranges are also indicated.

The range of participant VA is shown in figure 6.11. The majority of participants are shown to have a binocular logMAR VA of 0.10 or better. The presence of cataract is similar for all VA groups except for those with the best VA, where as expected, cataract prevalence rates are not as high.

The results obtained via CSC measurement were tested for normality using values for skewness and kurtosis. Here a value of zero for both measures would indicate perfect normality to the data. Skewness is a measure of how symmetrical a probability distribution for a random variable is about its mean. Kurtosis measures how steep or flat the peak of the same distribution curve is. Values of + or -2 for both skewness and kurtosis are considered acceptable to prove a normal univariate distribution (George 2011). With the CSC results most of the data, except for some of the CSCNG and VA scores was shown to follow a normal distribution using values of skewness and kurtosis (see table 6.4). A Kolmogorov-Smirnov analysis was also used to test for normality. Using this procedure all the data collected were shown to be non-parametric. However more weight was given to the results of skewness and kurtosis in this instance as the Kolmogorov-Smirnov test has been shown to be strongly influenced by larger sample sizes (Field 2009).

If a data set is skewed the mean loses its ability to provide the best central location for the data. This is because the skewed data drags the calculable mean away from the true typical value. As such median and inter-quartile range (IQR) data is presented for the CSC scores which were not found to be normally distributed. For those that were shown to be normally distributed, mean and standard deviation (SD) results are normally presented. However providing median results for certain test scores and mean results for others would make comparisons difficult. It was therefore decided to present median and IQR results for all groups (see table 6.5).

Table 6.4 showing the values for skewness, kurtosis and the results generated from the Kolmogorov-Smirnov test. The results are presented for each of the groups used in the study and for all CSC and VA scores. The values of skewness and kurtosis that would indicate the data is not normally distributed are highlighted in red.

| | Skewness | Kurtosis | Kolmogorov-Smirnov |
|---|---|---|---|
| **CSC all data** | | | |
| CSCNG | -1.65 | 3.14 | P < 0.001 |
| CSCG | -0.85 | 1.64 | p < 0.001 |
| CSCDG | 0.63 | 0.65 | p < 0.001 |
| VA | 0.85 | 0.41 | p < 0.001 |
| **CSC Young** | | | |
| CSCNG | -1.48 | 1.28 | p < 0.001 |
| CSCG | -0.49 | -0.24 | p < 0.001 |
| CSCDG | 1.36 | 5.29 | p < 0.001 |
| VA | 1.83 | 5.46 | p < 0.001 |
| **CSC Old** | | | |
| CSCNG | -1.38 | 1.95 | p < 0.001 |
| CSCG | -0.98 | 1.86 | p < 0.001 |
| CSCDG | 0.46 | 0.56 | p < 0.001 |
| VA | 0.58 | 0.09 | p < 0.001 |
| **CSC No cataract** | | | |
| CSCNG | -1.91 | 4.43 | p < 0.001 |
| CSCG | -0.25 | -0.44 | p < 0.001 |
| CSCDG | 0.66 | 2.00 | p < 0.001 |
| VA | 1.19 | 1.96 | p < 0.001 |
| **CSC Cataract** | | | |
| CSCNG | -1.24 | 1.56 | p < 0.001 |
| CSCG | -1.42 | 2.00 | p < 0.001 |
| CSCDG | 0.64 | -0.06 | p < 0.001 |
| VA | 0.19 | 0.55 | p = 0.20 |

Table 6.5 showing the median and IQR for all CSC scores and VA results. Median and IQR results are presented for all test scores to make comparisons between participant groups more straightforward.

| | Median | IQR |
|---|---|---|
| **CSC Overall (n = 361, Ave age 57 years, range 18-96 years)** | | |
| CSCNG | 1.65 | 1.50-1.65 |
| CSCG | 1.20 | 1.05-1.35 |
| CSCDG | 0.45 | 0.30-0.60 |
| VA | -0.04 | -0.12-0.04 |
| **CSC young (n = 156, Ave age 38 years, range 18-59)** | | |
| CSCNG | 1.65 | 1.50-1.65 |
| CSCG | 1.35 | 1.20-1.50 |
| CSCDG | 0.30 | 0.15-0.45 |
| VA | -0.12 | -0.18-0.06 |
| **CSC old (n = 205, Ave age 72 years, range 60-96 years)** | | |
| CSCNG | 1.65 | 1.50-1.65 |
| CSCG | 1.05 | 0.90-1.20 |
| CSCDG | 0.60 | 0.45-0.60 |
| VA | 0.02 | -0.06-0.12 |
| **CSC 2 no cataract (n = 258, Ave age 50 years, range 18-84 years)** | | |
| CSCNG | 1.65 | 1.50-1.65 |
| CSCG | 1.20 | 1.05-1.35 |
| CSCDG | 0.30 | 0.30-0.45 |
| VA | -0.08 | -0.14-0.02 |
| **CSC cataract (n = 76, Ave age 74 years, range 45-89)** | | |
| CSCNG | 1.50 | 1.50-1.65 |
| CSCG | 0.90 | 0.75-1.05 |
| CSCDG | 0.60 | 0.60-0.75 |
| VA | 0.10 | 0.02-0.20 |

The results shown in Table 6.5 for the CSC show good variation in participant performance between glare and no glare scores and that the majority of people in the young and no cataract groups were now reaching the 11 o'clock letter (with the lowest contrast) in the CSCNG condition.

Table 6.6 shows strong statistically significant differences between the young and old groups (under and over 60 years) and those with and without cataract. An independent samples t-test and a Mann-Whitney analysis were both carried out on all the data. Cohen's d was used to investigate the effect size (importance of the effect between each group of participants) and a previously developed estimate of effect size for non-parametric data was also completed (Rosenthal et al. 1994). As the groups were two independent samples, a pooled SD was used to calculate this measure (Field 2009). Parametric and non-parametric testing was initiated as skewness and kurtosis results indicated normality to most of the data. These strongly significant differences were found using VA results and all CSC scores, for both parametric and non-parametric testing. The CSCNG scores show a lower effect size than do the other clock scores. This was most likely due to the ceiling effect produced with the CSC design as the majority of participants, even the majority of participants with cataract, were now correctly identifying the maximum CS value. The difference between each group for CSCNG scores show moderate effect sizes whereas the other test measures show large effect sizes. The CSCG and CSCDG scores taken from the cataract and no cataract groups show a very large effect size between groups, the cataract group being close to two standard deviations away from the no cataract group scores (Field 2009).

Table 6.6 showing how age and cataract affect participant performance when measuring both CSC and VA scores. Both the t-test and Mann-Whitney test were used to test for statistical significance between groups. The difference between groups showed the same statistical significance when using both parametric and non-parametric testing. The effect size was calculated using Cohen's d analysis and also a non-parametric comparison.

| Participant groups | CSCNG | CSCG | CSCDG | VA |
|---|---|---|---|---|
| **CSC** | | | | |
| **Young/old** | | | | |
| z-score | -4.28 | -11.49 | -10.43 | -10.47 |
| p-value | $p < 0.001$ | $p < 0.001$ | $p < 0.001$ | $p < 0.001$ |
| t-score | 4.71 | 12.88 | -11.75 | -11.05 |
| p-value | $p < 0.001$ | $p < 0.001$ | $p < 0.001$ | $p < 0.001$ |
| Cohen's d | 0.49 | 1.38 | 1.25 | 1.14 |
| Cohen's d estimate | 0.45 | 1.50 | 1.28 | 1.32 |
| **Cataract/no cataract** | | | | |
| z-score | -3.82 | -11.01 | -10.59 | -8.98 |
| t-score | 4.02 | 14.39 | -13.95 | -11.08 |
| p-value | $p < 0.001$ | $p < 0.001$ | $p < 0.001$ | $p < 0.001$ |
| Cohen's d | 0.45 | 1.89 | 1.79 | 0.84 |
| Cohen's d estimate | 0.43 | 1.50 | 1.42 | 1.12 |

By convention a medium effect size is shown by a Cohen's d score of ≥ 0.50 and a large effect size by a score ≥ 0.80 (Cohen 1988). A Cohen's d above 0.80 indicates the mean difference between two groups differs by more than 8/10 of the pooled standard deviation. Effect sizes with low to medium practical significance are highlighted in green, those with high practical significance are highlighted in red.

Iris colour was recorded to see if pigmentation had an impact on the amount of intraocular light scatter an individual was likely to experience. For this analysis those given an iris grade of one (light iris colour) were compared to those with an Iris colour of four or five (dark iris colour) by way of the iris classification scale used (Seddon et al. 1990). All participants with cataract and other ocular pathology were removed from this analysis and groups were age-matched. It was only possible to appropriately age match data from 30 participants. Therefore the CSC data from the 30 participants with dark irises who could be successfully matched was used and compared to a randomly chosen subset of 30 participants who had light coloured irises. No statistical significant difference in CSCG and CSCDG performance was observed between those with light or those with dark irides when using the Mann-Whitney test, ($z = -1.39$, $p = 0.17$) and ($z = -0.98$, $p = 0.33$) respectively. The Mann- Whitney test was used as Kolmogorov-Smirnov analysis showed all data to be non-parametric for both groups ($p < 0.001$).

The CSC was next tested in terms of its validity, discriminative ability and whether a CSC score gave additional information beyond VA regarding perceived driving difficulty.

### *6.3.1 Validity*

Validity is an investigation of whether a device actually measures what it purports to measure (Elliott and Bullimore 1993). Normally a test or device is classed as a 'gold standard' or reference measure, against which any other test designed to measure the same variable can be judged. In the field of straylight and glare no definitive gold standard exists, although some have used the straylight meter (Elliott and Bullimore 1993; van Rijn et al. 2005). Previously the validity of devices measuring CS and glare in cataract patients has also been assessed using perceived visual performance (Koch 1989; Elliott et al. 1990a). The present study is concerned with the visual performance of the driving population and how this is affected by cataract. As such a questionnaire particularly designed for this task would appear to be most appropriate. However as previously discussed few driving specific questionnaires for people with cataract exist and those that do, show poor psychometric performance (Khadka et al. 2013). The two driving questions on the distance/lighting/reading subscale of the better performing VDA questionnaire were therefore used in order to see how these correlated with CSC scores.The two questions were as follows:

To what extent, if at all, does your vision interfere with your ability to drive a car by day? And secondly drive a car by night?

Table 6.7 showing the number (and percentage) of responses in each response category to the two different driving questions on the distance/lighting/reading subscale of the VDA questionnaire. The responses are split by participant group (see appendices for full questionnaire)

| **Response categories** | **not at all 1** | **a little 2** | **quite a bit 3** | **a lot 4** |
|---|---|---|---|---|
| ***Young participants (n = 156, Ave age 38 years, range 18-59)*** | | | | |
| Drive by day | 141 (90%) | 11 (7%) | 1 (1%) | 3 (2%) |
| Drive by night | 96 (62%) | 44 (28%) | 12 (8%) | 4 (2%) |
| ***Old participants (n = 205, Ave age 72 years, range 60-96 years)*** | | | | |
| Drive by day | 197 (96%) | 7 (3%) | 0 (0%) | 1 (<1%) |
| Drive by night | 121 (59%) | 56 (27%) | 19 (9%) | 9 (5%) |
| ***Non-cataractous participants (n = 258, Ave age 50 years, range 18-84 years)*** | | | | |
| Drive by day | 243 (94%) | 11 (4%) | 1 (<1%) | 3 (1%) |
| Drive by night | 173 (67%) | 64 (25%) | 17 (7%) | 4 (1%) |
| ***Cataractous participants (n = 76, Ave age 74 years, range 45-89)*** | | | | |
| Drive by day | 71 (93%) | 4 (5%) | 0 (0%) | 1 (2%) |
| Drive by night | 31 (41%) | 28 (37%) | 11 (15%) | 6 (7%) |

Table 6.7 shows the number of responses by each group of participants in each response category. As can be seen by the table, there are a minimal number of responses in the categories describing the most severe symptoms. The great majority of respondents reported minimal problems and scored 1 on the questionnaire, showing a large floor effect. Daytime driving scores were 1 for 94% of the sample and provided minimally useful information. Night-time driving provided more useful scores, with 40% reporting some difficulty (a score > 1). As would be expected, the participants in the cataract group reported greater problems with driving, especially at night. Specific driving-related questions, taken from a larger questionnaire have previously been used to investigate possible associations with performance on vision tests (van Rijn et al. 2002; van Rijn et al. 2005; van den Berg et al. 2009b). Driving difficulty by night responses were analysed separately to assess the strength of correlation with CSC results.

Questionnaires often use a Likert scale for data recording purposes. This type of scale produces a number of ordinal variables which are non-parametric in nature. Most statistical text books advocate the use of the Spearman test for calculating correlations between ordinal variables (Field 2009). Others have advocated the use of parametric statistics for Likert scale or non–normal distributions (Norman 2010). Therefore both Pearson and Spearman correlation coefficients have been calculated to test the strength of the correlations.

Table 6.8 Validity: Showing Pearson and Spearman correlation coefficients found between Contrast Sensitivity Clock (CSC2) scores and driving by night (DBN) questionnaire scores for all participants (n = 361). Skewness and kurtosis values indicate that all questionnaire responses were normally distributed, therefore mean (μ), standard deviation (σ) and the range of scores are also indicated.

| Test | Questionnaire correlation | |
|---|---|---|
| | Spearman *ρ* | Pearson |
| **CSC 2 - DBN (μ = 1.56, +/- 0.80, range 3)** | | |
| CSCNG | -0.12, $p = 0.02$ | -0.13, $p = 0.02$ |
| CSCG | -0.23, $p < 0.001$ | -0.26, $p < 0.001$ |
| CSDG | 0.23, $p < 0.001$ | 0.24, $p < 0.001$ |

The correlations highlighted in green were statistically significant to the $p < 0.05$ level and the correlations highlighted in red were statistically significant to the $p < 0.01$ level.

As can be seen by Table 6.8, the Spearman and Pearson correlations gave very similar values for all correlations tested. This supports the idea that parametric tests are robust when normality assumptions are violated (Norman 2010) and can be used without the risk of coming to inaccurate conclusions.

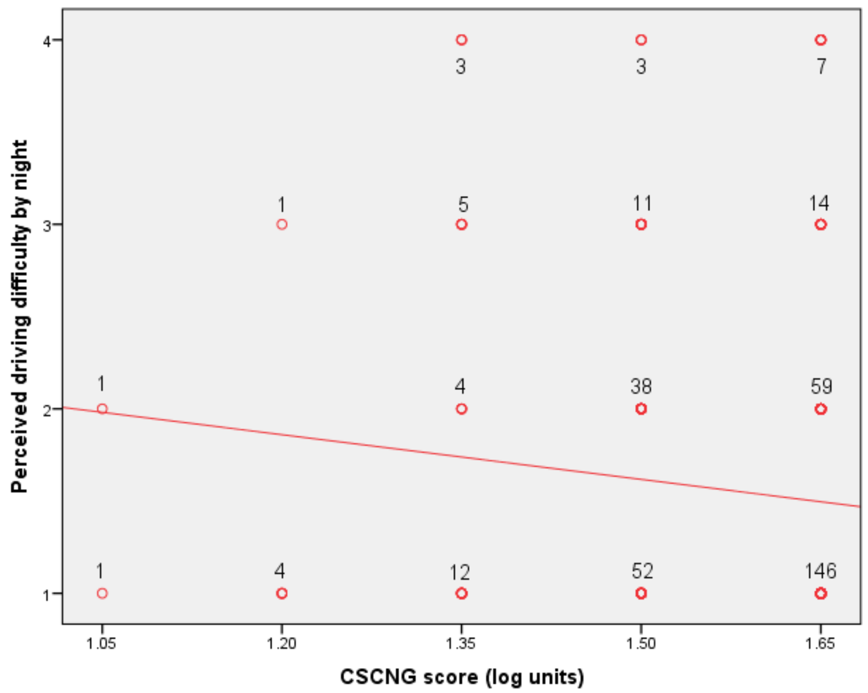


Figure 6.12 showing how CSCNG scores relate to perceived driving difficulty by night (Pearson r = -0.13, p = 0.02). The number of participants found at each data point is indicated. A floor effect is seen with the questionnaire scores where the majority of participants indicated no problems when driving at night. (A response of one would indicate no problems with vision when driving at night. A score of four would indicate major problems with vision when driving at night).

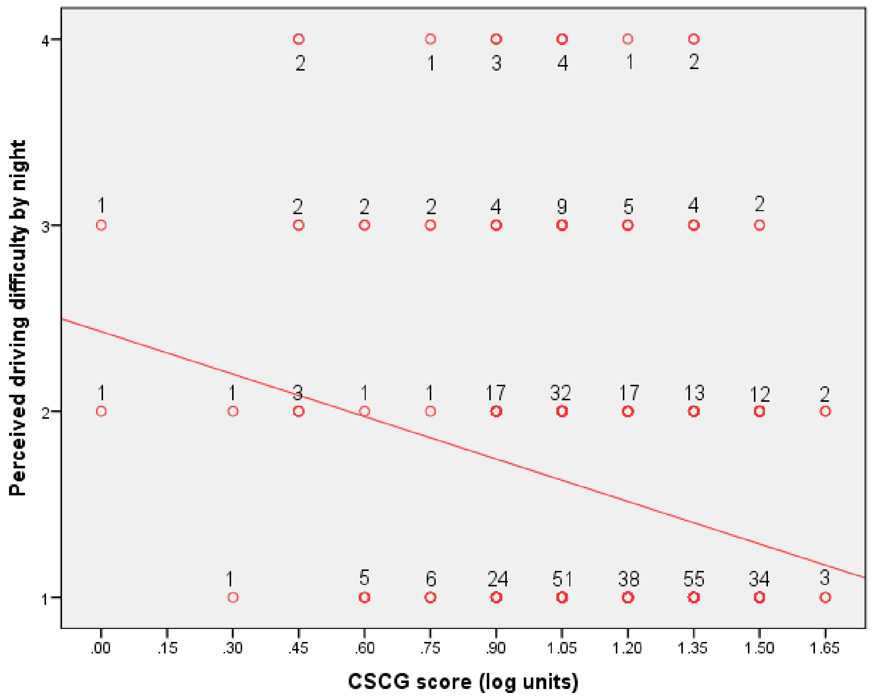


Figure 6.13 showing how CSCG scores relate to perceived driving difficulty by night (Pearson r = -0.26, p < 0.001). The number of participants found at each data point is indicated. Once again a floor effect is seen with the questionnaire scores where the majority of participants indicated no problems when driving at night. (A response of one would indicate no problems with vision when driving at night. A score of four would indicate major problems with vision when driving at night).

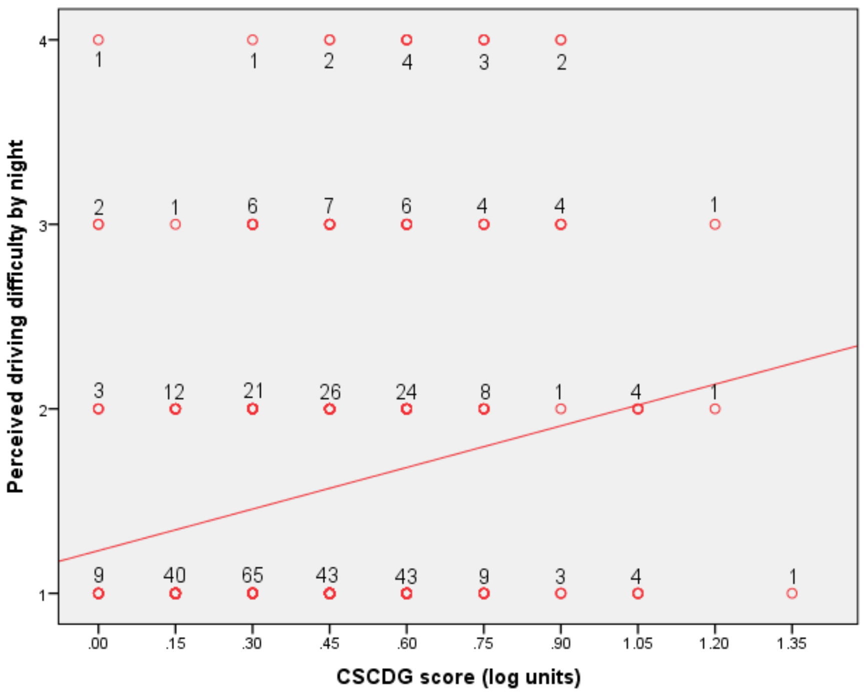


Figure 6.14 showing how CSCDG scores relate to perceived driving difficulty by night (Pearson r = -0.24, p < 0.001). The number of participants found at each data point is indicated. Once again a floor effect is seen with the questionnaire scores where the majority of participants indicated no problems when driving at night. (A response of one would indicate no problems with vision when driving at night. A score of four would indicate major problems with vision when driving at night).

Figures 6.12-6.14 show a visual representation of the correlations presented in table 6.8. On each figure the number of participants at each data point is indicated. As expected there are strong floor effects seen with the questionnaire responses as the majority of participants tested indicated no problems when driving at night.

### *6.3.2 Discriminative ability*

This describes how well a test or device is able to discriminate between normal and abnormal patients or different groups of people. Receiver operating characteristic (ROC) curves, which plot sensitivity (total number of true positives/total number of abnormal subjects) against 1 – specificity (where specificity is the number of true negatives/the number of true negatives + the number false positives), were calculated to assess this (Elliott and Bullimore 1993). The value for the area under the curve is given, where a score of 0.50 would be at chance level and a score of one would mean that the test is perfect at distinguishing between normal and abnormal patients.

The CSC was therefore assessed on its ability to discriminative between young/old participants and between those with and without cataract.

Table 6.9 Values for the area under the ROC curves for discriminating between the groups young/old and those with/without cataract.

| Test | Cataract vs no cataract | Young vs old |
|---|---|---|
| **CSC 2** | | |
| CSCNG | 0.61 | 0.61 |
| CSCDG | 0.87 | 0.81 |
| CSCG | 0.89 | 0.85 |

A value closer to 1 indicates the better discriminative ability of a test

Table 6.9 indicates the discriminative ability of the different clock scores at distinguishing between groups. It should be noted that the cataract and no cataract groups were not age-matched and therefore the effect seen above is not solely due to cataractous changes. Results show that CSCG scores are the superior measure for this purpose. CSCNG scores appear to be substantially less effective than the other CSC scores at distinguishing between each group, most likely attributable to the ceiling effect present for this measure. The CSC has been developed as a screening device to assess how a participant is affected by a glare source and not as a measure of contrast threshold. It is expected that the majority of participants would reach the maximum CSCNG value that the CSC can measure. The glare scores and DG scores are therefore of much more value as shown by both the discriminative ability and validity results generated. The CSCG scores were shown to be a significantly superior measure than CSCDG scores at discriminating between the groups above (Anova statistics for the discrimination between groups using CSCDG scores as a covariate measure: young/old groups $F = 4.56$, $p = 0.03$, cataract/no cataract $F = 6.34$, $p = 0.01$). Likely down to the ceiling effect seen with the CSCNG scores, artificially reduce the levels of DG in some people.

A full ROC analysis was also carried out on the CSC data, using a separate group of participants which included all those with pathology known to reduce visual function. Those previously classified as having cataract, PCO, AMD or Glaucoma were removed as well as participants who had poorer binocular VA than 6/12. This group of participants was termed “positive” as all members had indicators which could affect visual function. This separate analysis was undertaken as cataract is not the sole reason for reduced CS in the presence of glare in the driving population. Figure 6.15 below shows the ROC curve generated. The area under the curve was 0.88 showing the CSCG discriminated well between the positive group of participants and normals. The positive group contained 97 participants with a mean age of 74 +/- 9 years. The control group consisited of 264 participants with a mean age of 51 +/- 19 years. This means that age will also be a factor in the discriminative ability of the device as shown below.

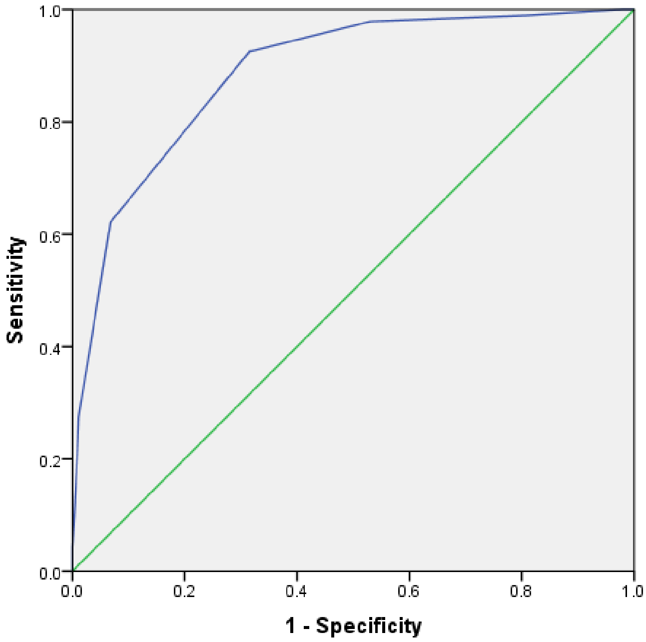


Figure 6.15 showing the ROC curve generated using the CSCG scores achieved by positive and normal groups of participant. The plotted curve illustrates the ability of CSCG scores to discriminate between the positive group of participants and those classified as normal (Area under curve (0.88).

Next a stepwise regression analysis was used with CSC and VA data to see which variable(s) gave most information about perceived driving difficulty at night. This was performed using the questionnaire responses to the driving by night question.

At step one of the analysis CSCG score was added into the regression equation and was significantly related to perceived driving difficulty by night $F (1, 359) = 25.01$, $p < 0.001$. The r-value was 0.26 and $r^2 = 0.07$ indicating that approximately 7% of the variance of perceived driving difficulty at night could be accounted for by CSCG score. No other variable, CSCDG score ($t = 0.04$, $p = 0.97$), VA ($t = 0.65$, $p = 0.51$) or CSCNG ($t = 0.25$, $p = 0.80$) entered the equation at step two of the analysis. Thus the regression equation for predicting perceived driving difficulty at night was:

**Perceived driving difficulty by night = -0.76 x CSCG + 2.43**

This analysis shows that CSCG score gives the most information when predicting perceived driving difficulty by night and that VA gives no additional information beyond this measure. The relationship between CSCG scores and perceived driving difficulty by night is highlighted in figure 6.13. A line of best fit is added to the data showing the strength of the relationship between points ($R^2$ = 0.07).

Other commercially available devices measuring levels of intraocular light scatter and DG have been assessed using similar methods. However, the results cannot be reliably compared as the questionnaire, the number of questions and group classification used for analysis with the CSC was different to that used with the other devices. It has also been shown that correlations can be hugely affected by the range of data used (Haegerstrom-Portnoy et al. 2000).

van Rijn et al. (2005) investigated the validity, discriminative ability and repeatability of the straylight meter (SLM), comparing its performance to the Nyktotest and Mesotest glare testers. As previously mentioned it is not possible to directly compare results from this study to those generated by van Rijn et al. However a separate analysis was done with the data collected from this study using a similar group classification to that used by van Rijn et al. This allowed an investigation into the discriminative ability of the CSC using groups that were more closely aged matched. The group classification used for this was as follows:

1) Young participants: - aged between 18 and 40, with VA of at least 0.1 logMAR in each eye and no ocular pathology (n = 70, mean age 26 +/- 7 years).
2) Old participants: - 50 years of age and older, with a VA of at least 0.1 logMAR in each eye and no other ocular pathology other than minor cataract (n = 63, mean age 62 +/- 7 years).
3) Cataractous participants: - cataract in at least one eye using the same cataract classification as previously described in this study, but this time monocularly. Cataractous participants were required to have a binocular VA of at least 0.2 logMAR with no other ocular disease (n = 61, mean age 74 +/- 6 years).

The data from participants who did not satisfy any of these criteria were eliminated from the data set.

Table 6.10 Values for the area under the ROC curves for discriminating between the groups young/elderly and those with cataract (n=194).

| Test (BE) | Cataract vs no cataract (young and elderly) | Cataract vs no cataract (elderly) | Elderly vs Young |
|---|---|---|---|
| **Data collected from this study** | | | |
| CSCG | 0.93 | 0.88 | 0.75 |
| CSCDG | 0.91 | 0.84 | 0.78 |
| VA | 0.92 | 0.90 | 0.68 |

A value closer to 1 indicates the better discriminative ability of a test

VA measures appear to discriminate well between cataractous and non-cataractous participants. They seem to have a tougher job discriminating between young and older normal participants, when compared to the different glare testers used. The ROC plots drawn up from the CSC data are shown below (figures 6.16-6.21).

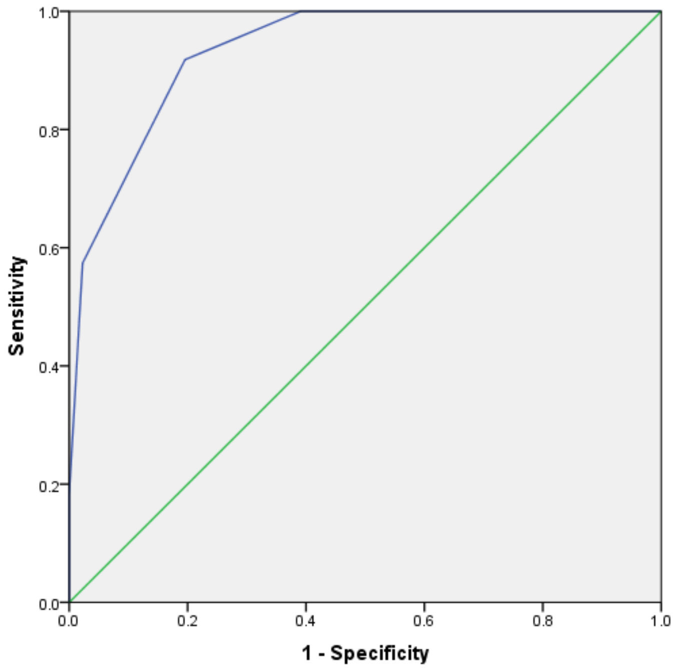


Figure 6.16 showing the ROC curve generated using the CSCG scores achieved by cataract and normal (young and elderly) groups of participant. The plotted curve illustrates the ability of CSCG scores to discriminate between groups (Area under curve 0.94). The green reference line indicates where discriminative ability is at chance level.

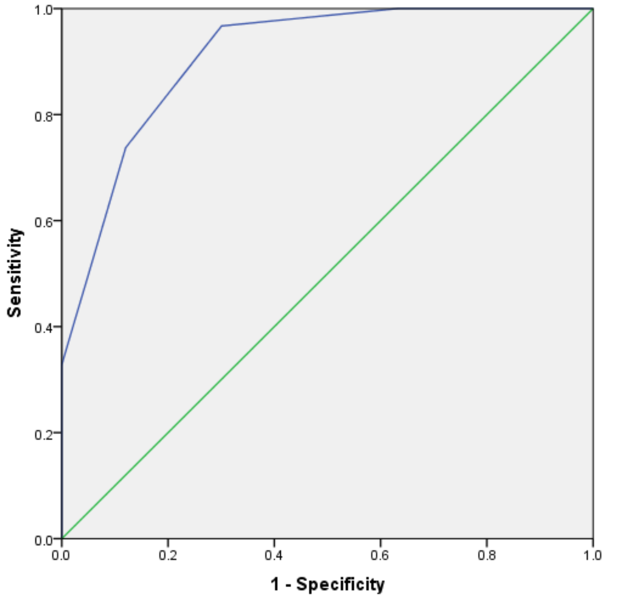


Figure 6.17 showing the ROC curve generated using the CSCDG scores achieved by cataract and normal (young and elderly) groups of participant. The plotted curve illustrates the ability of CSCDG scores to discriminate between groups (Area under curve 0.91). The green reference line indicates where discriminative ability is at chance level.

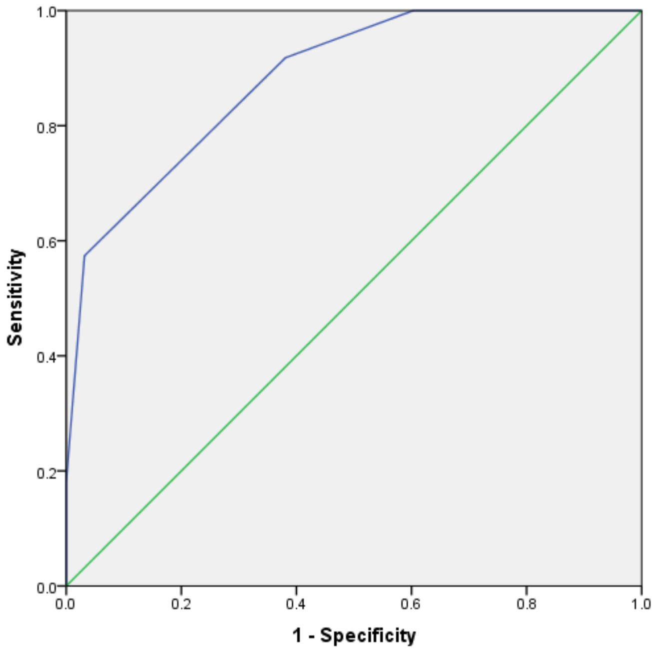


Figure 6.18 showing the ROC curve generated using the CSCG scores achieved by cataract and elderly normal groups of participant. The plotted curve illustrates the ability of CSCG scores to discriminate between groups (Area under curve 0.88). The green reference line indicates where discriminative ability is at chance level.

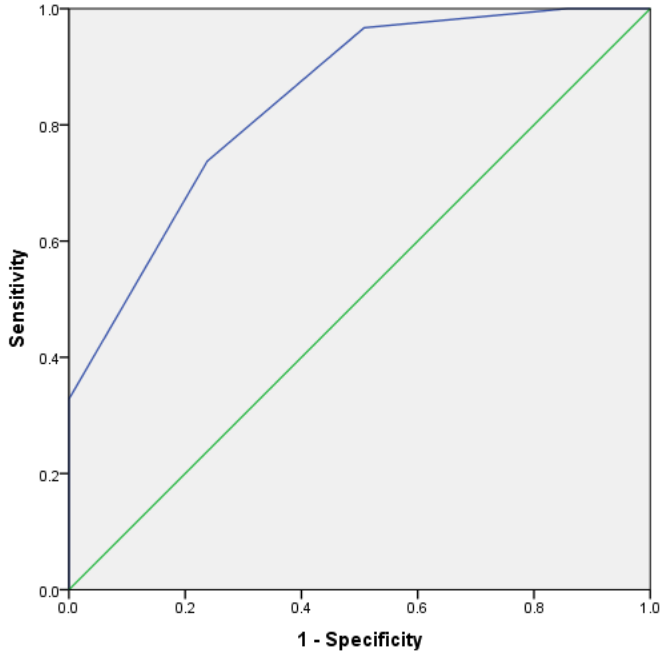


Figure 6.19 showing the ROC curve generated using the CSCDG scores achieved by cataract and elderly normal groups of participant. The plotted curve illustrates the ability of CSCDG scores to discriminate between groups (Area under curve 0.84). The green reference line indicates where discriminative ability is at chance level.

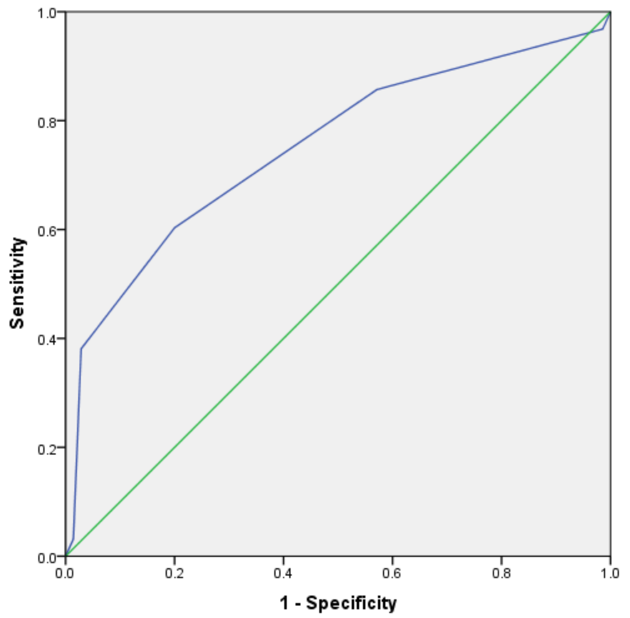


Figure 6.20 showing the ROC curve generated using the CSCG scores achieved by young and elderly normal groups of participant. The plotted curve illustrates the ability of CSCG scores to discriminate between groups (Area under curve 0.75). The green reference line indicates where discriminative ability is at chance level.

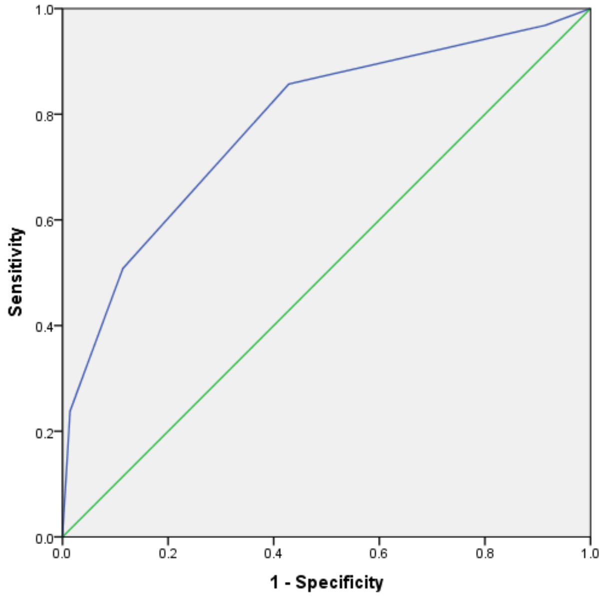


Figure 6.21 showing the ROC curve generated using the CSCDG scores achieved by young and elderly normal groups of participant. The plotted curve illustrates the ability of CSCDG scores to discriminate between groups (Area under curve 0.78). The green reference line indicates where discriminative ability is at chance level.

### *6.3.3 Rasch analysis*

Analysis of the questionnaire response categories showed that the options 'not at all', 'a little', 'quite a bit' and 'a lot' followed the intended hierarchy for 7/8 of the items, demonstrating a stepwise change in ability from response option to response option. The responses for the question regarding 'driving by night' was the only item not to follow this intended hierarchy with responses 'quite a bit' and 'a lot' appearing to cause some confusion. Analysis also appeared to show that the response category of 'a lot' was used very sparsely by participants for all items, with only 1% of overall questionnaire responses falling into this response category. It was therefore decided to merge response categories three and four in the hope of increasing patient separation. This had the desired effect, increasing separation slightly. With these two response categories merged there were still only 6% of overall participant responses in this upper item category. Patient separation could be increased further by merging response categories two, three and four. After these changes were made, item separation was (> 2) showing reliable item ordering (Tabrett and Latham 2011). However even after the aforementioned changes, person separation was still shown to be low (< 2). This means the questionnaire as it stands was poor at discriminating between different levels of participant ability found in the current study (Pesudovs et al. 2007).

Fit statistics were next carried out on the data in order to try and identify any mis-fitting items. The item regarding difficulty reading was shown to be a mis-fitting item with infit mean square values outside the acceptable range of 0.7-1.3 (Pesudovs et al. 2010). The elimination of this item improved person separation and also decreased the distance between person and item means, justifying its removal (Vianya-Estopa et al. 2010). Reducing the difference between mean person location and mean item location improves the targeting of the questionnaire to the participant sample (i.e. matching the difficulty of items to the ability of participants) (Pesudovs et al. 2010).

The PCA analysis showed the eigenvalue for the 1$^{st}$ contrast to be 1.4. Eigenvalues of 2.0 (Gothwal et al. 2009) and even 3.0 (Marella et al. 2009) for the 1$^{st}$ contrast have previously been used to show uni-dimensionality. Therefore uni-dimensionality was assumed.

Table 6.11 showing Rasch analysis data for the visual disability assessment (VDA) questionnaire distance/lighting/reading subscale. Results are shown after the aforementioned changes were made.

| | **Values** |
|---|---|
| **No. of items** | **8** |
| **No. of mis-fitting items removed** | **1** |
| **Person separation** | **0.92** |
| **Item separation** | **8.23** |
| **Mean person location** | **-2.08** |
| **PCA analysis-1$^{st}$ contrast eigenvalue** | **1.44** |

The full questionnaire scores for every participant who took part in this study were used to investigate how these related to CSCG scores. The fully Rasch analysed questionnaire scores were calculated, using the weightings given to each response category for each item. Figure 6.22 shows the relationship between CSCG scores and how the questionnaire was completed. As can be seen there is no real relationship between these two measures. The CSCG scores account for around 2% of the variance in questionnaire responses.

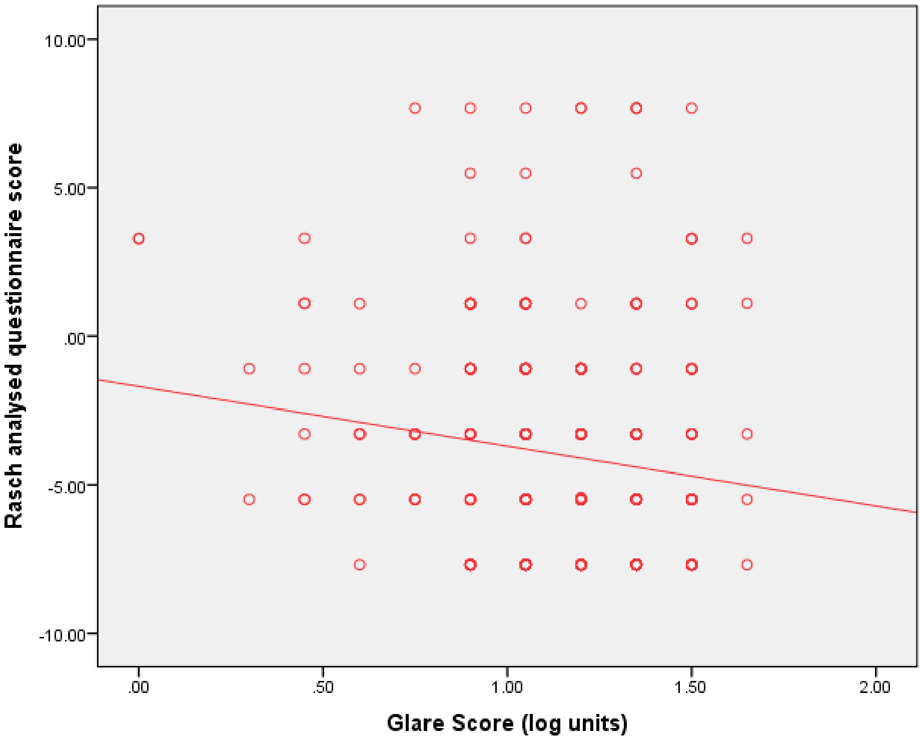


Figure 6.22 showing the relationship between CSCG scores and the participant responses from the fully Rasch analysed questionnaire scores. There is a very weak relationship between measures ($R^2$ = 0.02). The CSCG score accounts for around 2% of the variance seen in questionnaire responses.

Table 6.12 showing the mean and standard deviation glare score for each Rasch value generated from questionnaire responses.

| Rasch value | Mean and SD CSCG score |
|---|---|
| 7.68 (n = 9) | 1.18 +/- 0.24 |
| 5.49 (n = 3) | 1.10 +/- 0.23 |
| 3.30 (n = 5) | 1.02 +/- 0.43 |
| 3.29 (n = 4) | 0.75 +/- 0.87 |
| 3.28 (n = 1) | 1.50 +/- 0.00 |
| 1.11 (n = 6) | 1.00 +/- 0.48 |
| 1.10 (n = 23) | 1.12 +/- 0.24 |
| 1.09 (n = 2) | 0.90 +/- 0.00 |
| -1.09 (n = 37) | 1.07 +/- 0.26 |
| -1.10 (n = 7) | 1.22 +/- 0.22 |
| -3.29 (n = 59) | 1.14 +/- 0.26 |
| -3.30 (n = 8) | 1.09 +/- 0.19 |
| -3.31 (n = 1) | 1.20 +/- 0.00 |
| -5.49 (n = 82) | 1.14 +/- 0.27 |
| -5.50 (n = 2) | 1.20 +/- 0.42 |
| -7.69 (n = 32) | 1.44 +/- 0.08 |

Figure 6.22 and Table 6.13 show little correlation between CSCG scores and the Rasch analysed questionnaire data. The mean CSCG scores are very similar across all Rasch values. The only visible trend seen in table 6.13 is for those who responded that they had no problems with any of the tasks mentioned in the questionnaire. These participants scored -7.69 on the Rasch analysed questionnaire and on average achieved a slightly higher CSCG score than others.

As previously discussed a differential item functioning (DIF) analysis is normally used to examine whether item difficulty is the same across different sub-groups of participant. Minimal DIF was seen between the young and old participants for the item ‘recognising faces from across the street’ and notable DIF for the item ‘see in the distance’. For no cataract and cataract groups of participants minimal DIF was observed for the items ‘see in the distance’, ‘recognise faces from across the street’, ‘see in bright light or glare’ and ‘see in poor or dim light’. Notable DIF was observed for the questionnaire item ‘drive by night’. This would indicate that the questionnaire responses should be analysed separately for different groups of participant.

However, the completed Rasch analysis of the questionnaire data shows that the VDA distance/lighting/reading subscale was not suitable for use with the group of participants found in this study. Previous studies which have evaluated this questionnaire have done so with participants who have more severe cataractous changes (Pesudovs et al. 2010; McAlinden et al. 2011a; Khadka et al. 2013). Therefore the full Rasch analysis was re-done on the questionnaire data, solely from the cataract group of participants.

Table 6.13 showing Rasch results for the cataract group of participants (n = 76).

| **Groups** | **Cataract** |
|---|---|
| **No. of items** | **8** |
| **No. of miss-fitting items removed** | **0** |
| **Person separation** | **1.04** |
| **Item separation** | **3.99** |
| **Mean person separation** | **-1.69** |
| **PCA analysis-1$^{st}$ contrast eigenvalue** | **1.99** |

The person separation and the targeting of patient ability to item difficulty were slightly better for the cataract group, as would be expected. However, even in this instance the questionnaire is poor at discriminating between different levels of participant performance and the questions are poorly targeted to the ability of participants.

## 6.4 Discussion

Data for this study were collected using the original CSC 1 design and the amended CSC 2 design. The design changes made to CSC 1 increased the amount of DG produced by the device and improved its overall performance, both in terms of its validity and discriminative abiity. Repeatability is another important factor, maybe the most important when considering any device used for measurement. If repeatability is poor it normally follows that discriminative ability and validity are also poor (Elliott and Bullimore 1993). The repeatability of the CSC was therefore investigated and the results presented in chapter 7.

During this study cataract classification was based on the least affected eye as previously described. Other similar studies have based measurement on single eyes (Maraini et al. 1994; Chua et al. 2004; Stifter et al. 2004; van den Berg et al. 2007; Michael et al. 2009; Bal et al. 2011; Shandiz et al. 2011; Cheng et al. 2013) and so have not considered binocular status. Driving is a binocular task and therefore it would seem only right to measure the visual performance of participants used in this study in the binocular condition. Binocular CS has been shown to be superior than monocular measurements in situations where the two eyes have similar CS (binocular summation) whereas if there is a large difference between the two eyes binocular inhibition can occur, where the binocular performance falls to a level that is below the better monocular eye (Gilchrist and Pardhan 1987; Pardhan and Gilchrist 1990b; Azen et al. 2002). It has previously been suggested that binocular CS should be tested in uni-ocular cataract patients (Pardhan and Gilchrist 1991). The presence of bi-lateral cataract was also shown to be associated significantly with poorer vision-specific functioning, an effect not seen with uni-lateral lens changes (Chew et al. 2012).

It is not possible to directly compare validity and discriminative ability of the CSC to the other devices in the van Rijn et al. (2005) study due to different questionnaires and scoring systems being used and vague descriptions of their cataract participants ( “Clinically relevant cataract in at least one eye”). Another consideration would be that best corrected VA was used in the van Rijn study whereas habitual VA was used in the present study. This may also have influenced results, likely making discrimination between cataract and non-cataract groups more difficult in this current study as more advanced cataractous changes may have been excluded from the data set on grounds of VA, due to habitual correction being used. For these reasons it is not possible to directly compare data.

Iris colour is another factor that has previously been shown to have an impact on the amount of intraocular light scatter an individual experiences. People with lighter irises have been shown to suffer from greater amounts of straylight than those with darker irises (IJspeert et al. 1990; Nischler et al. 2013). The difference in amounts of straylight between different ocular pigmentations was found to be greater at larger glare angles (IJspeert et al. 1990). Differences in CS were found to be clinically negligible between different groups based on iris pigmentation (Nischler et al. 2013). In this study no significant differences in CSCDG or CSCG scores were found between aged matched groups of participants with light and dark irises. This finding is most likely due to measuring a CS score and not a direct measure of straylight as was the case in the aforementioned studies. A glare source is also much more effective close to fixation. With the CSC, the stimulus is surrounded by a ‘glare field’ of the same mean luminance, starting close to fixation and extending to larger angles. Therefore light scatter produced from larger glare angles where a difference in ocular pigmentation is reported to be responsible for greater differences in straylight may be of negligible importance when testing with the CSC. The lack of a significant difference found with the CSCDG scores could also be due to the ceiling effect seen with the CSCNG scores. This would have the effect of reducing the 'true' DG experienced by some of the participants.

Studies have previously examined how vehicle crash rates are affected by levels of CS and glare. Results from these are mixed. Some show levels of DG to be a good predictor of crash rates (Lachenmayr et al. 1998; Rubin et al. 2007) others do not (Ball et al. 1993; Owsley et al. 2001). Owsley et al. (2001) reported that in a cataract population someone with a recent crash history was eight times more likely to have seriously impaired CS in their worse eye. They measured visual function monocularly when binocular measures may have been more appropriate. Ball et al. (1993) used the Vistech MCT-8000 to measure DG which was shown to have serious limitations in its testing ability

(Elliott and Bullimore 1993). Owsley et al. (2001) analysed their data using two distinct groups for participant classification. Those with significant DG (≥ 0.25 log units) and those without (< 0.25 log units) and therefore may have missed more subtle changes. These reasons may go some way to explain why no link was found between DG and crash rates in these studies.

Driver performance studies involving assessment of driving performance have been more consistent with their findings, that those with greater DG show impaired driving performance (Ranney et al. 2000; Theeuwes et al. 2002; Wood et al. 2012). These studies help to reinforce the idea that CS and DG are important factors to consider when discussing driving standards.

CSCG scores are shown to be significantly superior than DG scores when assessing the discriminative ability and validity of the CSC. One consideration when assessing CSC results would be whether to use CSCG scores, CSCDG scores or a combination of the two. CS with glare scores are better than DG scores for assessing cataract patients who have normal visual function (Elliott et al. 1991b) in agreement with the results obtained from this study. As the CSCG scores are slightly superior than CSCDG scores at discriminating between groups, a conclusion may be drawn that CSCG results would be best to use for participant assessment. However, one advantage of using DG over CS with glare scores is that DG results are not influenced by post-optical factors in the same way. If a participant had cataract and AMD for instance, the CS with glare score could well be influenced by both pathologies and you would be unsure as to how much of an affect both were having. DG scores should not be affected by any retinal or neural abnormality and therefore you could be more sure of the affect cataract was having on visual function (Elliott and Bullimore 1993).

One main consideration for the developers of any new test or device is the identification of an appropriate pass/fail level for the purposes required. An ROC analysis was completed in order to assess how well the CSC discriminated between the normal and “positive” groups of participant (figure 6.15). The sensitivity and 1-specificity data obtained during this analysis enabled an appropriate pass/fail level to be considered. When using ROC data the sensitivity of the test is concerned with the number of false negative results with a value of 1 indicating an absence of false negatives. The specificity is concerned with the number of false positives where a value of 0 on the 1-specificity axis would indicate no false positive results. Sensitivity is also of limited importance in this instance as we do not want to highlight everyone with ocular pathology, only those most affected by glare. The presence of ocular pathology does not necessarily mean that CS in the presence of glare is going to be reduced to a significant level. Therefore high sensitivity to this “positive” population is not a pre-requisite. If a CSCG score of ≤ 0.75 log units was used as the point where someone would fail the test then the CSC would have a sensitivity of 0.27 and a 1-specificity value of 0.01 or 99% specificity. This point was chosen as after this the number of false positives would rise much more dramatically if a higher pass/fail CS were chosen. This would keep false positive values low while still offering reasonable sensitivity using our patient sample, highlighting a good proportion of the driving population most affected by glare. This would also be the case when considering the entire driving population if the actual number of older people who were unsafe to drive due to glare were found in similar proportions. In this situation 14% of the older population would be required to stop driving. Therefore out of every 1000 people, 140 should stop and the CSC would successfully identify 37 of them. Out of the remaining 860, 1% of these would be false positives, equating to 8 people. This means 45 people would be detected and 37 (82%) of these would have a problem. However, if the actual proportion of the older population who were unsafe to drive was only 1%, 10 out of every 1000 people should stop and the CSC would identify only three of these. Of the remaining 990 people, approximately 10 of these would be false positives. This would mean that 13 people would be identified and 3 of these (23%) would actually have a problem. In this situation the pass/fail criteria would need to be re-examined and highlights the difficulty when setting an appropriate pass/fail level.  The number of false postives a test would generate is the most important consideration when assessing driving standards, as driving cessation could have a huge impact on an individual (DeCarlo et al. 2003)

.

In this study the total CS loss is of greater importance than what is attributing to the loss. DG score as a second measure does not add any additional value to this pass/fail criteria. This finding is not altogether unsurprising. If every participant were to reach the last letter in the CSCNG condition then CSCDG scores would directly match their CSCG scores offering no additional information. Every participant tested did not reach the last letter in the CSCNG condition, however the strong ceiling effect limits the amount of additional information given by CSCDG scores. CSCG score would therefore appear to be the most relevant measure when assessing whether someone would pass or fail the CSC.

### *6.4.1 Study limitations*

In the initial design phase of this study the light boxes sourced were rectangular in shape. This means, as shown in figure 6.2 there is potential for more glare to be produced at some points than others. It is not expected that his would have a meaningful effect. In the 12 and six o'clock postions on the clock, where the distance to the edge of the light box is at its most narrow, the space is still 2.5-3 times the height of the letters used. However it may be prudent in the future to further investigate whether clock position has a bearing on ease of letter identification. There may have also been a more appropriate letter size or working distance that could have been employed during the design phase and/or data collection. The most influential spatial frequency for letter correct letter identification would appear to be 1.5-2 cycles per letter width (Legge et al. 1985). At the time of testing the letters were found to equate to around 3cpd at the working distance used, where a spatial frequency of between 1.9-2.5cpd may have been more appropriate in order to satisfy this criteria. For future testing this could and maybe should be amended.

One of the main limitations of this study was the fact that the participants used were not dilated for LOCS III classification purposes, something recommended by the team who developed this classification scale (Chylack et al. 1993b). Dilation of participants was not undertaken due to the relatively large sample size used. Though far from ideal, other large sample size studies which have investigated measures of visual function in those with cataract have also carried out classification un-dilated (van den Berg et al. 2007; Michael et al. 2009; Nischler et al. 2010; van Rijn et al. 2011). The fact that participants were not dilated during this study may have influenced the results in some way. Validity results would remain unchanged but non-dilation could have affected the results for discriminative ability. It is difficult to say if any underestimation of cortical or PSC cataract would likely help or hinder our CSC results due to people being mis-classified. In the present study, different groups were compared on the basis of this same scoring and so little error will result, but the data cannot directly be compared with other studies that do use dilation (van den Berg et al. 2007).

The second main limitation found in this study was the questionnaire used for assessing perceived driving difficulty and subsequently the validity of the CSC. During the initial design phase of this study it was decided that the validity, discriminative ability and repeatability of the CSC was to be assessed. The main consideration in this chapter was therefore how to assess the device validity. A few other studies previously proposed the use of the CSLM as a gold standard and therefore something the validity of other devices could be tested against (Elliott and Bullimore 1993; van Rijn et al. 2005), but as driving is a binocular task for most and the CSLM tests monocularly this would limit its usefulness in this situation. The previously highlighted binocular summation or inhibition (Pardhan and Gilchrist 1990a; Pardhan 1993) that can occur when viewing with the two eyes together rather than monocularly would appear to be justification for this. Questionnaire responses of perceived visual impairment, have also been used to assess device validity (Koch 1989; Elliott et al. 1990a; van Rijn et al. 2005). As this technique would assess participants in a real world binocular state and because the CSLM is not a universally accepted gold standard device it was decided a questionnaire would best assess device validity for the purpose required.

Cataract by its very nature produces a greater amount of light scatter (van Rijn et al. 2005; van den Berg et al. 2009b). Therefore a questionnaire was chosen that was particularly targeted to this population. The questionnaire also needed to incorporate questions about driving and particularly driving at night as this is a situation where large amounts of DG could have serious ramifications.

McAlinden et al. (2011a) compared 16 regularly used questionnaires for pre and post cataract surgery via Rasch analysis in order to test performance. The Catquest-9SF questionnaire was shown to perform best but did not incorporate any questions about driving difficulty. The next most responsive (ability to detect clinically important differences) was the VDA and its three different sub-scales.

Khadka et al. (2013) compared 48 different patient reported outcome questionnaires to test which had the highest psychometric quality. In those particularly targeted to cataract patients once again the CatQuest-9SF was shown to perform best followed by the VDA questionnaire. The RSVP questionnaire had a subscale particularly targeted to driving however this questionnaire fared poorly in relation to the VDA. The distance/lighting/reading sub-scale of the VDA was shown to be a valid, unidimensional measure (Pesudovs et al. 2010), incorporating two questions about perceived driving difficulty and was therefore used in this study.

Rasch analysis was performed on the questionnaire responses and weightings generated for each question and category of response. These weightings were used instead of the original one, two, three or four values given to each question response in order to calculate correlations with CSC and VA scores. Correlations with the DBN questionnaire scores were stronger when compared to correlations seen with the Rasch analysed questionnaire. The questions the distance/lighting/reading subscale incorporates, were found to be poorly targeted to participant ability. The questions corresponded to visual symptoms that were too severe for the average participant in our sample to endorse and as such the discriminative ability of the questionnaire to distinguish between different levels of participant ability was poor. In hindsight a questionnaire showing a unidimensional construct exactly matching the intentions of this study would have been more appropriate.  Using the best performing questionnaire which included questions about driving but was poorly targeted to the participant sample was a design error. The design of a new questionnaire specifically for purpose may also have improved results generated from questionnaire responses. Kimlin et al. (2016) recently developed a new questionnaire designed specifically for drivers over 50 years of age who report low luminance, glare or adaptation concerns about their vision when driving at night. Although developed too late for this study, future work would be advised to employ a questionnaire such as this, directly aimed at the participant group in question.

Other studies looking at associations between glare and driving have not undertaken Rasch analysis on their questionnaire responses. They appear to have taken specific driving related questions from a questionnaire and analyzed these responses separately (McGwin et al. 2000; van Rijn et al. 2005; Michael et al. 2009; van den Berg et al. 2009b) in order to show task dependent difficulty. The problem with using a full questionnaire or sub-scale is that most available are developed to show vision related quality of life and not task specific difficulties (van Rijn et al. 2002). Questions regarding other DV and NV tasks have been shown to correlate poorly with responses to perceived driving difficulty at night (van Rijn et al. 2002) and would therefore likely have a detrimental effect on any correlations seen with this task. It has been suggested that the best way to show condition dependent disability and to reduce response variability between participants was to subtract the driving by day questionnaire score from driving by night questionnaire scores (van Rijn et al. 2002). During this study the questionnaire data was not analysed in this way as the methodology above has not been widely used in similar research.

### *6.4.2 Summary*

There is growing belief that CS and DG, among other measures of visual function, should be considered when investigating fitness to drive in certain people. The CSC appears to fulfill its remit of being a cheap, quick, valid and discriminative test and results compare favourably against other more established tests used in this area. The repeatability of the CSC needs to be examined and direct performance comparisons with other devices would be useful before the CSC could be widely implemented. However, results from this study show promise that it could one day become a viable device for assessing how susceptible a person is to glare.

# 7.0 Assessing the repeatability of the contrast sensitivity clock

## 7.1 Introduction

The CSC was developed to try and cost effectively and quickly assess how an individual's CS is affected by a glare source. The CSC was previously shown to be both a valid measurement (reports what it purports to measure) and a discriminative test (good at distinguishing between normal and abnormal patients). This study will attempt to analyse the repeatability of the device.

Clinical research has advocated that all clinical tests be evaluated on their validity, discriminative ability and repeatability (Elliott and Bullimore 1993). Repeatability is arguably the most important way to evaluate a new device, with its discriminative ability and validity being somewhat dependant on the repeatability of a test (Elliott and Bullimore 1993). Repeatability refers to the variation in repeated measures, recorded from the same subject under identical conditions (Taylor 2009). All readings should be recorded using the same measurement technique, from the same examiner, over a short period of time and at the same location. If all these conditions are met any variation in test scores from the same participant can be attributed to errors in the measurement process itself (Bartlett and Frost 2008). Typically results recorded from each participant are taken on two occasions, spaced by a week or so (Elliott and Bullimore 1993).

Previously the repeatability of a device has been presented in terms of the inter-subject variability in test scores for normal participants (Corwin and Richman 1986; Ginsburg et al. 1987) or by the examination of test and re-test scores via correlation coefficients (Ross et al. 1985; Long and Tuck 1988). Both methods are not ideal. It is not unusual for different 'normal' participants to exhibit different performance levels on clinical tests. Performance levels can be influenced by both optical and neurological factors (Elliott and Bullimore 1993) and therefore assessment of device repeatability using this method is limited. Correlation coefficients are also questionable in their suitability for repeatability assessment as they are influenced by the range of scores used (Bland and Altman 1986). They show association rather than agreement between scores (Bland and Altman 1986) and are not equated in the units of the measurement being tested, therefore having limited clinical applicability (Bartlett and Frost 2008; Vaz et al. 2013). A more appropriate way of assessing performance would be to use the coefficient of repeatability (RC). The RC describes the 95% confidence limits between any observed changes in test to re-test data (Elliott et al. 1990b) where the difference between two measurements from the same subject are not expected to differ by more than the RC on 95% of occasions (Bartlett and Frost 2008). The RC is recorded in the units being tested by the particular device used.

During this study 30 participants were tested with two different versions of the CSC in order to test the devices repeatability. Repeatability results were directly compared to a more established device used for measuring CS and glare. The Pelli-Robson (PR) chart was used in conjunction with the BAT. This method has been used extensively in previous literature (Elliott et al. 1990a; Elliott and Bullimore 1993; Lasa et al. 1993; Rubin et al. 1997; Owsley et al. 2001; Rubin et al. 2007).

## 7.2 Methods

30 participants were tested from the University of Bradford student cohort and the more regular attending volunteer patients from the University eye clinic. This made up a convenience sample. The group of participants used in this chapter was similar in size and makeup to those used in previous studies, where the repeatability of devices measuring similar visual function was assessed (Elliott et al. 1990b; Elliott and Bullimore 1993; van Rijn et al. 2005; Buckhurst et al. 2015). Ethical approval was obtained from the University of Bradford ethics committee and the study followed the tenets of the Declaration of Helsinki. Participants were again required to have habitually corrected binocular Snellen VA of at least 6/15. The participants were between 20-83 years old, with a mean age of 46 +/- 22 years.

The experimental methodology for this study largely followed those described during chapter 6, but logMAR VA was measured using the Thomson test chart 2000 (Thomson Software Solutions) to ensure participants met the VA requirement previously set. Measurement took place at a distance of 6m and ceased when the participant incorrectly identified three letters or more on a single line. As previous a slit lamp examination was carried out and a LOCS III cataract classification (Chylack et al. 1993b) was recorded for every participant. The earliest cataractous changes have been shown to occur from the age of 40 years (The Eye Diseases Prevalence Research 2004). Therefore in a change from the methods used during chapter 6, participants over the age of 40 years were dilated using a 0.5% tropicamide solution. At the end of the assessment a leaflet regarding the drops that were instilled was given to the participant.

Dilation allows as full an assessment of any cataract present as possible. A Volk lens was used to assess the health of the posterior pole.

Participants were tested with two versions of the CSC on two separate occasions, separated by at least one week. All participants were seen for a second time within three weeks of their first assessment. The participants' habitual correction was used during the study once the spectacles had been cleaned and checked for significant scratches.

| Clock Time | Actual CS | CS score | Grey level | No glare letters | Glare letters |
|---|---|---|---|---|---|
| 12 | 0 | 0 | 37.77 | H | S |
| 1 | 0.075 | 0.15 | 56.66 | S | D |
| 2 | 0.225 | 0.30 | 65.88 | K | R |
| 3 | 0.375 | 0.45 | 73.93 | D | N |
| 4 | 0.525 | 0.60 | 78.88 | R | Z |
| 5 | 0.675 | 0.75 | 82.21 | Z | N |
| 6 | 0.825 | 0.90 | 84.60 | N | V |
| 7 | 0.975 | 1.05 | 86.39 | V | H |
| 8 | 1.125 | 1.20 | 87.79 | Z | K |
| 9 | 1.275 | 1.35 | 88.91 | S | S |
| 10 | 1.425 | 1.50 | 89.83 | N | Z |
| 11 | 1.575 | 1.65 | 90.60 | K | R |

| Clock Time | Actual CS | CS score | Grey level | No glare letters | Glare letters |
|---|---|---|---|---|---|
| 12 | 0 | 0 | 37.77 | H | S |
| 1 | 0.075 | 0.15 | 56.66 | V | H |
| 2 | 0.225 | 0.30 | 65.88 | R | V |
| 3 | 0.375 | 0.45 | 73.93 | H | Z |
| 4 | 0.525 | 0.60 | 78.88 | S | H |
| 5 | 0.675 | 0.75 | 82.21 | K | R |
| 6 | 0.825 | 0.90 | 84.60 | D | K |
| 7 | 0.975 | 1.05 | 86.39 | N | S |
| 8 | 1.125 | 1.20 | 87.79 | S | V |
| 9 | 1.275 | 1.35 | 88.91 | V | R |
| 10 | 1.425 | 1.50 | 89.83 | H | H |
| 11 | 1.575 | 1.65 | 90.60 | D | Z |

Figure 7.1 showing the different letters used on the two separate versions of the CSC.

Testing was otherwise carried out as previously described in chapter 6, with participants once again grouped by age and the presence of cataract. Iris colour classification and questionnaire responses were not recorded during this study.

Repeatability results were compared to the performance of the PR chart (Pelli et al. 1988) used in conjunction with the brightness acuity tester (BAT) (Holladay et al. 1987) at its medium glare setting (measured at 330cd/m$^2$ by direct photometer readings). The medium glare setting was used as the high setting was previously shown to give inappropriately high predictions of glare sensitivity (Neumann et al. 1988; Prager et al. 1989).


Figure 7.2 showing both versions of the Pelli-Robson chart used for data collection.

PR CS was recorded both with and without the BAT, enabling a monocular CS score; a CS with glare score and a DG score to be recorded for every participant. Once again the results were repeated with the second version of the PR chart with visits separated by at least a week (again everyone was seen for their second assessment within 3 weeks of their first visit). Pre-presbyopic participants were required to complete the task with their habitual distance correction in place. As some of the presbyopic participants were wearing multifocal spectacles, the distance correction from their most recent pair of glasses was incorporated into a trial frame using full aperture trial case lenses. This spectacle prescription was taken from eye clinic records or if not available from focimetry of their current glasses. VA was then re-taken. Testing was carried out at a distance of 1m and therefore presbyopic participants had a

+0.75D lens incorporated into the prescription they were wearing (Elliott et al. 1990b). The PR charts used were checked for fading prior to use by way of direct photometer readings. Participants were again given adequate time to recover from glare effects throughout the procedure.

As the BAT is a monocular glare tester the repeatability results recorded from the PR chart were made using the participant’s dominant eye. The fellow eye was covered using a standard black opaque occluder.

The PR chart uses triplets of letters at the same CS level. Each subsequent triplet represents a CS of 0.15 log units greater than the previous.

| | | | |
|---|---|---|---|
| **0.00** | **HSZ** | **DSN** | **0.15** |
| **0.30** | **CKR** | **ZVR** | **0.45** |
| **0.60** | **NDC** | **OSK** | **0.75** |
| **0.90** | **OZK** | **VHZ** | **1.05** |
| **1.20** | **NHO** | **NRD** | **1.35** |
| **1.50** | **VRC** | **OVH** | **1.65** |
| **1.80** | **CDS** | **NDC** | **1.95** |
| **2.10** | **KVZ** | **OHR** | **2.25** |

Figure 7.3 showing the letter scoring system used by the PR chart. Each letter making up a triplet of letters carries the same CS level. The numbers indicate the CS level of each triplet measured in log units.

Each individual letter was given a score of 0.05 log units (Elliott and Bullimore 1993) and measurement ceased when a participant volunteered two or three letters incorrectly at a particular CS level (Elliott et al. 1990c). Participants were asked to study the letters for 15-20 seconds and then encouraged to guess around their threshold level (Elliott et al. 1990b). The charts used had a mean luminance of 80cd/$m^2$ measured via direct photometry as per the manufacturer's guidelines. The order in which the tests were completed was randomised for each participant.

### 7.3 Results

Figure 7.4 is presented below showing the age range of participants used in this study.

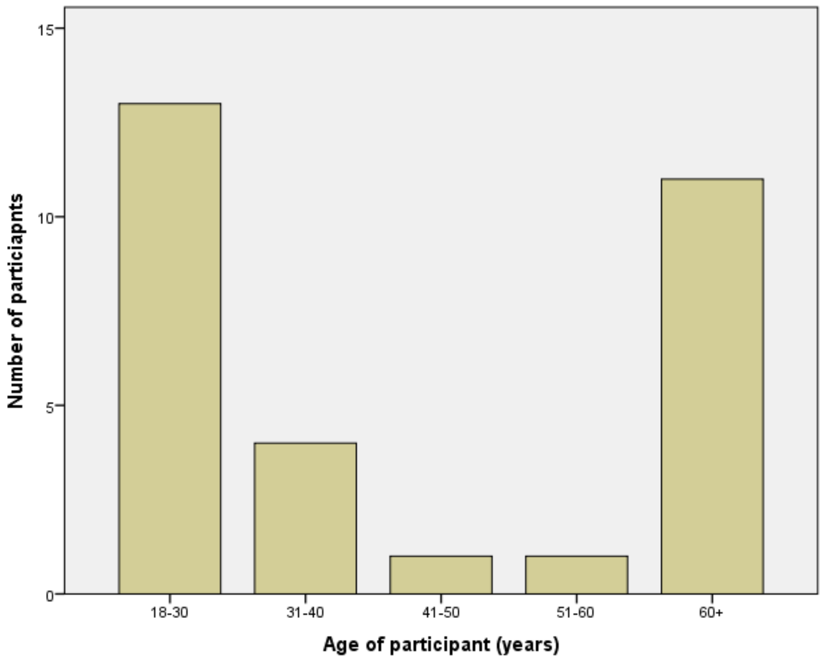


Figure 7.4 showing the age range of participant used during the repeatability study. Most vast majority of participants were either below 30 or over 60 years.

The Kolmogorov-Smirnov test was used in order to establish whether the data obtained were normally distributed. This was done for each group of participant and each measure of visual function. Kolmogorov-Smirnov results are presented in table 7.1.

Table 7.1 showing values obtained after Kolmogorov-Smirnov analysis, testing for normality to the data. Values are shown for both versions of the CSC and PR chart for no glare, glare, DG and VA scores.

| | All (n = 30) | Young (n = 19) | Old (n = 11) | Cataract (n = 5) |
|---|---|---|---|---|
| **CSC A** | | | | |
| NG | p < 0.001 | p < 0.001 | p < 0.001 | p = 0.001 |
| G | p = 0.001 | p = 0.002 | p = 0.20 | p = 0.022 |
| DG | p < 0.001 | p < 0.001 | p = 0.20 | p = 0.20 |
| **CSC B** | | | | |
| NG | p < 0.001 | p < 0.001 | p < 0.001 | p < 0.001 |
| G | p < 0.001 | p < 0.001 | p = 0.20 | p = 0.20 |
| DG | p < 0.001 | p < 0.001 | p = 0.20 | p = 0.20 |
| **PR A** | | | | |
| NG | p = 0.001 | p = 0.006 | p = 0.020 | p = 0.053 |
| G | p < 0.001 | p = 0.024 | p = 0.20 | p = 0.11 |
| DG | p = 0.019 | p = 0.009 | p = 0.117 | p = 0.20 |
| **PR B** | | | | |
| NG | p = 0.001 | p = 0.001 | p = 0.20 | p = 0.20 |
| G | p = 0.005 | p = 0.001 | p = 0.032 | p = 0.16 |
| DG | p = 0.013 | p = 0.021 | p = 0.20 | p = 0.20 |
| **VA** | p < 0.001 | p = 0.001 | p = 0.20 | p = 0.15 |

A p value above 0.05 would indicate normality to the data

The results obtained from the Kolmogorov-Smirnov analysis indicate normality to some of the data but not all. Therefore mean/median and inter quartile range/standard deviations are reported where appropriate. These are presented in table 7.2. As there is a ceiling effect seen with the CSCNG scores, they have limited value when used on their own. However they are included in the results presented here

Table 7.2 showing the median/mean and IQR/SD for binocular CSCNG, CSCG, CSCDG and VA scores (logMAR). All results are presented in log units. The data is shown for the participant sample as a whole and the separately for the young, old and cataract groups.

| | CSC A | | CSC B | |
|---|---|---|---|---|
| | Median/Mean | IQR/SD | Median/Mean | IQR/SD |
| **All participants (n = 30)** | | | | |
| **NG** | **1.65** | **1.65-1.65** | **1.65** | **1.65-1.65** |
| **G** | **1.35** | **1.05-1.50** | **1.35** | **1.20-1.35** |
| **DG** | **0.30** | **0.15-0.45** | **0.30** | **0.30-0.45** |
| **VA** | **-0.16** | **-0.10-(-0.20)** | | |
| **Young participants (n = 19)** | | | | |
| **NG** | **1.65** | **1.58-1.65** | **1.65** | **1.65-1.65** |
| **G** | **1.35** | **1.35-1.50** | **1.35** | **1.35-1.43** |
| **DG** | **0.15** | **0.15-0.30** | **0.30** | **0.23-0.30** |
| **VA** | **-0.16** | **-0.14-(-0.20)** | | |
| **Old Participants (n = 11)** | | | | |
| **NG** | **1.65** | **1.65-1.65** | **1.65** | **1.50-1.65** |
| **G** | **1.02** | **+/-0.28** | **0.97** | **+/-0.28** |
| **DG** | **0.59** | **+/-0.30** | **0.61** | **+/-0.24** |
| **VA** | **0.01** | **+/-0.19** | | |
| **Cataract participants (n = 5)** | | | | |
| **NG** | **1.65** | **1.50-1.65** | **1.65** | **1.65-1.65** |
| **G** | **0.90** | **0.75-0.98** | **0.90** | **+/-0.24** |
| **DG** | **0.72** | **+/-0.22** | **0.75** | **+/-0.24** |
| **VA** | **-0.03** | **+/-0.22** | | |

Table 7.3 showing the median/mean and IQR/SD data for monocular PRNG, PRG and PRDG scores presented on log units. The data is shown for the participant sample as a whole and the separately for the young, old and cataract groups. VA is not included in this table as results are shown in table 7.4.

| | Pelli-Robson A | | Pelli-Robson B | |
|---|---|---|---|---|
| | Median/Mean | IQR/SD | Median/Mean | IQR/SD |
| **All participants (n = 30)** | | | | |
| **NG** | **1.70** | **1.65-1.85** | **1.68** | **1.65-1.80** |
| **G** | **1.65** | **1.55-1.70** | **1.65** | **1.50-1.65** |
| **DG** | **0.15** | **0.05-0.20** | **0.15** | **0.00-0.15** |
| **Young participants (n = 19)** | | | | |
| **NG** | **1.75** | **1.73-1.88** | **1.75** | **1.70-1.85** |
| **G** | **1.70** | **1.70-1.75** | **1.70** | **1.65-1.70** |
| **DG** | **0.05** | **0.00-0.15** | **0.05** | **0.00-0.15** |
| **Old Participants (n = 11)** | | | | |
| **NG** | **1.67** | **+/-0.16** | **1.69** | **+/-0.13** |
| **G** | **1.47** | **+/-0.24** | **1.50** | **1.50-1.65** |
| **DG** | **0.20** | **+/-0.13** | **0.16** | **+/-0.10** |
| **Cataract participants (n = 5)** | | | | |
| **NG** | **1.63** | **+/-0.18** | **1.66** | **+/-0.11** |
| **G** | **1.35** | **+/-0.26** | **1.50** | **+/-0.18** |
| **DG** | **0.28** | **+/-0.13** | **0.16** | **+/-0.12** |

Tables 7.2 and 7.3 show how the results differed between tests and the different versions of the same device. If we look at the differences between both versions of the CSC in table 7.2 all results are very similar for each group of participant. This is also the case between the two versions of the PR chart shown in table 7.3. For both the CSC and the PR chart one CS step size is

equal to 0.15 log units. Considering each group of participant separately, all median scores for each device were within one step size of each other.

Discrepancies in CS results have been shown between different tests (Bühren et al. 2006). As such it is not possible to directly compare CS or CS with glare results from different devices. The DG scores involve the difference between two scores from the same measurement technique and therefore can be more easily compared. From tables 7.2 and 7.3 above, it is clear that the CSC produces much more of a DG effect on participants than does the PR chart used in conjunction with the BAT. There is also a much greater difference in DG scores between the performance of the young and cataract groups with the CSC.

In previous research correlation coefficients between test and re-test data have been used as an assessment of device repeatability (Ross et al. 1985; Long and Tuck 1988; Elliott and Bullimore 1993). Pearson correlation coefficients are now presented. Parametric statistics have been shown to be extremely resilient to errors that may be caused when data is non-normally distributed (Norman 2010). Using Pearson correlation coefficients also allows direct comparison to previous literature.

Table 7.4 showing Pearson correlation coefficients between repeated CSC and PR measures.

| | CSC | PR |
|---|---|---|
| CSNG score | r = 0.15 | r = 0.75 |
| CSG score | r = 0.85 | r = 0.77 |
| DG score | r = 0.83 | r = 0.50 |

Correlation coefficients highlighted in red were statistically significant ($p < 0.01$)

The correlation coefficient results involving glare were stronger for the CSC than the PR chart when used with the BAT. When CS scores were examined without glare the correlation coefficient with the PR chart was much stronger than the result obtained from the CSC. This is due to the ceiling effect seen with the CSCNG scores, reducing the range of values recorded. Although the glare results from the CSC are similar, the correlation coefficient from the PRDG scores seems to be somewhat weaker than from the PRG scores. This finding is not unexpected due to the smaller range in PRDG scores. The range of DG scores recorded from the CSC results is the same as the range seen with the CSCG scores. This goes some way to explaining why the correlation coefficient seen with CSCDG scores is higher.

Bland-Altman plots were next drawn up showing the level of agreement between test and re-test scores recorded from the CSCG scores (figure 7.5). The 95% confidence limits were drawn showing the 95% of the test re-test data points were within 2 step sizes on the CSC. A linear regression analysis was run in order to assess if there was any proportional bias of the number of points above or below the mean trend line shown in figure 7.5. No proportional bias was observed ($t = -0.10$, $p = 0.89$).

The same analysis was carried out for test and re-test Pelli-Robson scores in figure 7.6. Once more this shows that 95% of the data points were within 2 step sizes. Once again using a linear regression analysis, no proportional bias of data points above or below the mean line was observed (t = 1.04, p = 0.31).

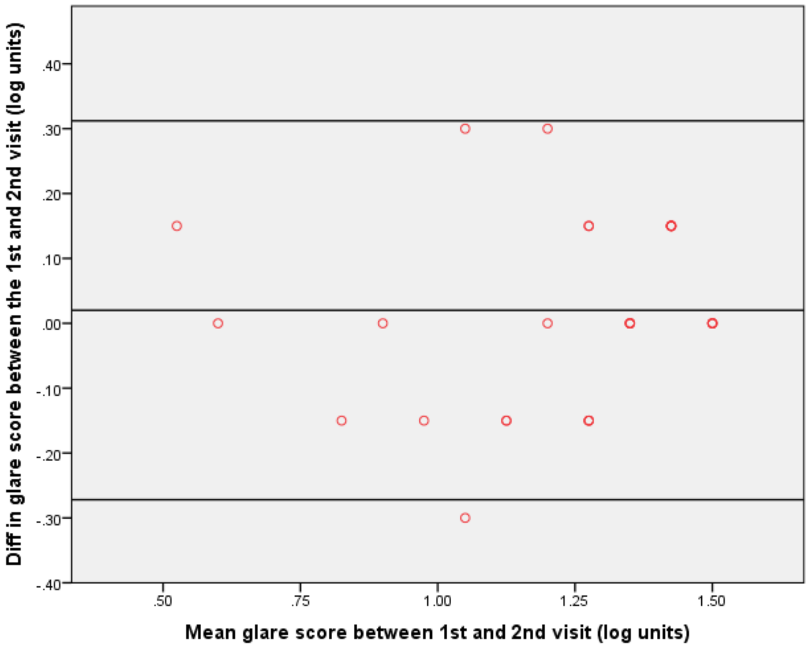


Figure 7.5 showing the Bland-Altman plot for repeated glare measures recorded from both versions of the CSC. The centre line indicates the mean difference between measures. The upper and lower lines represent the 95% confidence limits for the data.

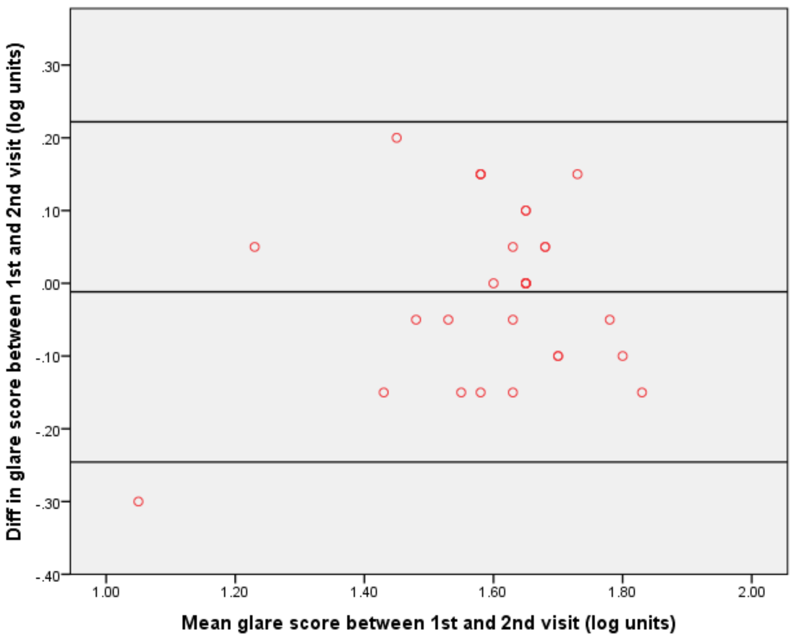


Figure 7.6 showing the Bland-Altman plot for repeated glare measures recorded from both versions the Pelli-Robson chart. The centre line indicated the mean difference and the upper and lower lines indicate the 95% confidence limits for the data.

The level of agreement between measurements can be better expressed in terms of the RC. The RC was calculated from the differences between the repeated measurements, RC = 2 x SD (standard deviation of the differences) (Bland and Altman 1986). In the NG condition most people were able to reach the last letter on the CSC producing a truncation to the results and potentially improving repeatability for both CSCNG and CSCDG scores. CSCNG scores have limited value when used on their own as most people are able to reach maximum CS. Therefore RC results were not calculated for this measure. The CSCDG results are presented but it should be noted that the truncation to CSCNG scores could influence RC results for this measure. In order to better compare repeatability with other devices measuring in different units the 95% confidence limits for change are presented for each device (Elliott et al. 1991a). The performance of the CSC was compared to PR scores with and without the

BAT and other devices from previous literature (van Rijn et al. 2005). The repeatability study completed by van Rijn was not specific when it came to the participants used for data collection. “In half the subjects glare and straylight measures were repeated on a different day” (van Rijn et al. 2005). The group classification used was previously described in chapter 6. However due to an absence of specific information, direct comparison of repeatability results from the different studies should only be done with caution.

Table 7.5 showing the RC values for the CSCG, CSCDG, PRG and PRDG scores (n = 30) and results previously obtained for the NSLM, Nyktotest with glare and Mesotest with glare (van Rijn et al. 2005). 95% confidence limits for change for each device are also included.

| Device | RC | RV | 95% confidence limits for change |
|---|---|---|---|
| CSCG | 0.29 | 1.05 | +/-0.45 |
| CSCDG | 0.30 | 1.05 | +/-0.45 |
| PRCS | 0.18 | 0.60 | +/-0.25 |
| PRG | 0.23 | 1.00 | +/-0.30 |
| PRDG | 0.24 | 0.55 | +/-0.30 |
| NSLM | 0.29 | 1.17 | +/-0.40 |
| Mesotest G | 1.41 | 4 | +/-3 |
| Nyktotest G | 1.52 | 8 | +/-3 |

The RC value shows the repeatability of the device in its own units. Values for the CSC seem to compare well to other tests designed for use in this area (van Rijn et al. 2005). RV is the total range of values recorded using each device.

The RC values for the CSCG scores show that on 95% of occasions repeated results from the same individual would not differ by more than ± 0.29 log units (two step sizes). This is the same for PR results which again appear to be repeatable to within two CS step sizes. However the PR chart has three decisions with each 0.15 log unit step compared to one decision with the CSC, likely to improve performance.

The 95% confidence limits for change that are presented in table 7.5 attempt to give an indication of what change is needed to give a significant change of test score (Elliott et al. 1991a). The RC for the CSC is within two step sizes meaning the 95% confidence limits for change would be +/-0.45 log units or three step sizes. This accounts for 25% of the scoring range. When using the glare involved PR chart measures the RC is again within two 0.15 log unit step sizes. However if the PR chart results are recorded using the letter by letter scoring system as described earlier, the 95% confidence limits for change would be reduced to +/-0.30 log units. This accounts for 13% of the scoring range improving performance. The NSLM measures in 0.05 log unit steps meaning the limits for change would be 0.35 log units, approximately 18% of the total measurement range. The Mesotest and Nyktotest would appear to show poorest repeatability with 95% confidence limits for change accounting for 75% and 38% of the entire measurement range respectively.

The discriminative ability of both tests was examined next using ROC curves. Results from both versions of the CSC and both versions of the PR chart were averaged to assess test discriminative ability. The glare and DG scores were used during this analysis.

Table 7.6 showing the average discriminative ability (test and re-test data) for the CSC and the PR chart at distinguishing between the young/old and cataract/no cataract participants.

| | Young/old | | cataract/no cataract | |
|---|---|---|---|---|
| | CS with glare | DG | CS with glare | DG |
| **CS clock** | **0.92** | **0.92** | **0.98** | **0.98** |
| **Pelli-Robson** | **0.82** | **0.81** | **0.94** | **0.85** |

The CSC and PR chart both appear to discriminate well between the groups of participants used in this study. Table 7.6 shows that both CSCG and CSCDG scores discriminate equally well between groups. As would be expected the ability to discriminate between cataract and non-cataract participants is slightly better than the ability to distinguish between the young and old groups. This trend is also seen with the PR data, where the discriminative ability is again slightly superior between cataract and non-cataract groups. With the PR data the PRG scores look to be better at discriminating between the cataract and non-cataract groups than do the PRDG scores. Again PRG and PRDG scores are very similar at discriminating between the young and old groups. The CSC scores seem to be slightly superior to the PR scores at discriminating between the groups of participant used in this study.

### 7.4 Discussion

In this study the CSCG scores were again shown to be slightly more discriminative and repeatable than CSCDG scores. The PR data also indicated that it was the PRG scores which performed slightly better than other PR test scores. For these reasons the discussion will be based on CS with glare results.

Repeatability is an essential quality of any measurement device and as previously mentioned is best presented in the form of the RC. The RC generated for the CSCG scores indicated that this measure was repeatable to ± 0.29 log units or to within two letters (two step sizes) on the CSC. The PRG scores were shown to be slightly more repeatable at ± 0.23 log units. Using a letter by letter scoring method this would show the PRG measure to be repeatable to within five letters or once again to within two CS step sizes using the more traditional scoring system. This result recorded for the PR chart and BAT agrees well with previous literature (Elliott et al. 1991a; Elliott and Bullimore 1993). Using the letter by letter scoring system instead of the system proposed by the manufacturer, was previously shown to improve the repeatability of the PR chart by a factor of two (Elliott et al. 1991a). This provides a finer step size for result recording which improves repeatability. Analysis of the 95% confidence limits for change would also indicate that the repeatability of the PR is superior to that of the CSC if letter by letter scoring is used. One obvious amendment to the design of the CSC would therefore be to try and reduce the increment between letters. The step size used with the CSC is larger than the letter by letter step size used with the PR chart and could be one of the main reasons why repeatability is slightly reduced.

The main issue with using RC values comes when attempting to directly compare results to other devices measured in different units. When attempting to compare devices, Elliott and Bullimore (1993) stated that correlation coefficients maybe more appropriate, particularly when used on the same patient sample and like for like results are examined (e.g. test scores with glare). Correlation coefficients are however strongly influenced by the range of scores seen (Bland and Altman 1986). The range of DG scores is generally reduced when compared to the range of CS with glare scores and as a result correlation coefficients are normally lower. RC results are normally more similar when the ranges of results differ. This is shown in the PR results from this study and in previous literature for other test methods (Elliott and Bullimore 1993). When like for like results are compared, the range of values seen would hopefully be more consistent and therefore the correlation coefficients would give a more accurate idea when comparing test repeatability. In this study the range of values seen with the CSCG and PRG results were virtually identical. The correlation coefficient was found to be stronger for the CSCG scores than it was for the PRG scores. Values compare well with other devices measuring how glare affects vision (Elliott and Bullimore 1993).

More recently the ratio between the RC and the range of values (RV) has been used to compare the repeatability of different devices measuring different units (van Rijn et al. 2005; van den Berg et al. 2009b). This analysis would appear to give no other information above correlation coefficients which are at least reported routinely. This analysis was therefore not undertaken on the data recorded during this study.

The main consideration in a repeatability assessment is what exactly an acceptable level of repeatability would be. The CSCG scores for the 30 participants tested gave a RC of ± 0.29 log units meaning 95% of future scores given by the same participant would be within this range and a 95% confidence limit for change would be +/-0.45 log units. However whether this range is acceptable or not is open to debate. van den Berg et al. (2009b) stated that if normal scores from a device are well away from the cut off or fail value then a lower repeatability would be sufficient. If a ≤ 0.75 log unit CSCG score was used as a value that would fail the test as suggested in chapter 6, then the average young normal participant (< 60 years old with a CSCG score of 1.37 log units) and the average old normal participant (> 60 years old with a CSCG score of 1.20 log units) would be far enough away from the pass/fail level that errors in the measurement process would lead to few false positive results. The number of false positive results, in this case leading to possible driving cessation is a very important factor. The reduction in a patient's quality of life that such a restriction may cause could be tremendously detrimental (DeCarlo et al. 2003).

When using correlation coefficients there does not seem to be any common consensus as to what level a device should reach for tool selection (Hopkins 2000). Many studies cite Shrout and Fleiss (1979) to support claims that a clinically acceptable correlation should be above 0.75. This approach has been criticised by others for not assessing the usefulness of the recommended correlations (Hopkins 2000). As a general rule it has been suggested a correlation of 0.90 be considered as high, a value of 0.80-0.90 as moderate and anything below 0.80 as insufficient for an instrument involved in a decision making process (Vincent 1999; Hopkins 2000). CSCG scores satisfy this criterion. As mentioned previously even a high correlation between test and re-test data may be somewhat misleading (Vaz et al. 2013) and as such best practice guidelines recommend the use of correlation coefficients and RC values (Bland and Altman 2003; Lexell and Downham 2005).

Finally, results obtained with the PR chart initially appear slightly reduced when compared to previous studies (Elliott and Bullimore 1993; Mäntyjärvi and Laitinen 2001). One possible reason for this could be the lower chart luminance level used in the current study when compared to the two above. Also the median was used to describe the data used in the current study rather than the mean. Mean CS is slightly higher here than the median results (young participant CS with the PR chart, $\mu = 1.78$, +/-0.11 log units). There is also a difference in the make-up of participant groups between studies. For instance the young group here were significantly older ($\mu$ = 32.8, +/- 12.2 years) than in the study by Elliott and Bullimore and more varied in terms of age than the groups used by Mäntyjärvi and Laitinen. These factors would largely account for any discrepancies found.

### *7.4.1 Study limitations*

The CSC measurements in this study were made with the participants in a binocular state. The BAT measures glare monocularly and as such the dominant eye of each participant was used for PR measurement. Cataract classification was done, as in chapter 6, on the basis of cataract being present in both eyes. However it is possible that the visual function of an individual may alter between monocular and binocular status (Azen et al. 2002; Longley and Whitaker 2015). This factor should not affect the repeatability results as the same eye was used for both test and re-test data; however discriminative ability between the two devices should perhaps not be compared directly.

One issue which should be highlighted with the CSC is the apparent variability in the printing of the measurement sheets. Over the course of this project a number of different print options were assessed before the final format was decided upon. The HP Laserjet CM4540 proved to be the best option available for use. However there does seem to be visible variability in contrast levels if the CSC is re-printed a number of months after initial calibration. Therefore, as was the case in this study, the calibration procedure (chapter 6) should be re-done before printing to ensure grey levels are at the correct level for the different contrasts needed.

The participant sample size used in the current study was purely chosen as a convenience sample with a range of different subjects. The type of participant who would most likely be affected by glare would be the older cataractous population (Elliott and Bullimore 1993; van den Berg et al. 2009b). It therefore may have been more appropriate to target this type of participant for use in the repeatability study. This was considered, however as the CSC could theoretically be used with the whole driving population, a decision was made to investigate repeatability on young, old and cataract patients.

As previously stated the sample size and participant group make up for the repeatability study chosen was similar to previous studies evaluating similar devices (Elliott et al. 1991b; Elliott and Bullimore 1993; van Rijn et al. 2005; Buckhurst et al. 2015). However there is also a belief that repeatability studies involving similar sample sizes are more likely to identify false agreement between two methods. In order to reduce the likelihood of such findings it has been recommended that a sample size of at least 100 participants be used in agreement studies (McAlinden et al. 2011b). Therefore the participant sample size used in the current study may not have been large enough to provide accurate results.

#### ***Summary***

Currently, there is no real formulaic approach for deciding whether measurement error that occurs is acceptable or not (Vaz et al. 2013). From the analysis used in this study the repeatability performance of the CSC appears to be similar to other more established devices although slightly poorer than the

PR chart when used in conjunction with the BAT. One obvious way to improve repeatability further would be to reduce the step size used by the device. Despite this, even after measurement error is accounted for using the current version of the CSC, the numbers of false positive results are kept to a minimum using the pass/fail criteria suggested in chapter 6. The results here need to be corroborated by others and it would be necessary to carry out direct comparisons with more established devices before a full conclusion could be drawn. However the results to date would suggest the CSC to be a valid, discriminative and suitably repeatable test for assessment of how an individual is affected by a glare source.

# 8.0 Google Glass Glare: disability glare produced by a head-mounted visual display

## 8.1 Introduction

The global head mounted display (HMD) market was valued at $430.4 million dollars in 2012 and this is forecast to rise to $20,450.5 million dollars by the year 2022 (Transparency market research. 2015). Probably the most well-known example is Google Glass (Google Inc.) which aims to give users many of the advantages of a modern day smartphone in a hands-free, voice activated, and wearable format. Currently in a re-design phase, it uses an optical HMD, normally situated in front of the right eye and positioned above the visual axis in normal viewing. It can be linked to smartphones via Bluetooth or be connected to a local Wi-Fi signal from which contacts, messages, e-mails and apps can be downloaded.

Glass has been described extensively in previous literature (Nayak et al. 2014) and this along with other HMD devices offer several potential clinical advantages, including use as an aid for the visually impaired (Luo et al. 2009; Hwang and Peli 2014). However, the wearing of such a device may also lead to visual problems. Field defects caused by wearing HMD devices have been described (Woods et al. 2003; Ianchulev et al. 2014) and their use has been shown to critically alter a person's natural visual gait control (Mustonen et al. 2013). Distraction and attentional issues have also been highlighted, with the use of Glass for messaging resulting in impaired driving performance (Sawyer et al. 2014; He et al. 2015). In this study we examine another potential way in which normal visual function might be compromised during wear – that the display may act as a glare source resulting in DG due to intraocular light scatter. DG has been studied extensively (Paulsson and Sjostrand 1980; Vos 1984; IJspeert et al. 1990; van den Berg et al. 2013) and is well explained by light from a peripheral glare source being scattered by the ocular media, resulting in a veiling luminance which reduces the contrast of the retinal image (Paulsson and Sjostrand 1980; Vos 1984; Rubin et al. 1993; Whitaker et al. 1994). DG increases with age and exhibits an inverse square dependency on the eccentricity of the glare source from fixation (Vos 1984; Vos 2003a). Another important behaviour is that DG is governed by the ratio of the luminance of the glare source to the luminance of the stimulus that the observer is trying to view (Paulsson and Sjostrand 1980; Steen et al. 1993). The situation is exacerbated by the problem of oncoming car headlights when driving at night – this can produce a significant reduction in visual performance due to the low illuminance of the road ahead (Charman 1996; Wood et al. 2012; Gruber et al. 2013). The same headlights during daytime would produce negligible DG because of the brightness of the scene. For this reason, when considering the possible glare effects of an HMD, measurements need to be taken across a large range of luminance levels.

Most real-world glare sources create binocular DG, yet any glare arising from a HMD such as Glass is monocular in its effect. It may be thought that binocular visual performance would be dominated by the unaffected eye when vision in one eye is degraded. The treatment of presbyopia by contact lens wear using the monovision technique is an example where this appears to be the case (Evans 2007). In one epidemiological study binocular VA was shown to be correctly inferred from monocular measurements (Mangione et al. 2001).

However, there is also substantive evidence to suggest that this does not always hold true, due to a process known as ‘binocular inhibition’(Blake and Fox 1973; Gilchrist and Pardhan 1987; Azen et al. 2002), where binocular visual performance is significantly worse than in either eye on its own. This has been shown to occur when there is a significant difference between the two eyes, either through monocular blur (Pardhan and Gilchrist 1990b), reduced luminance in one eye (Fechner 1860; Gilchrist and Pardhan 1987), simulated glare superimposed on the retinal image of one eye (Pardhan and Gilchrist 1990a) or monocular cataract (Pardhan and Elliott 1991). More recent work has attempted to model the processes involved in interocular inhibition (Huang et al. 2011). For this reason, it is important to investigate both monocular *and* binocular visual performance in conditions where one eye is exposed to a glare source.

### 8.2 Equipment & Methods

The visual stimulus was a Gabor patch – a sinusoidal contrast grating of 1.7 cycles per degree windowed by a Gaussian having a spread (σ) of 0.311 degrees. A relatively low spatial frequency was used since previous studies have found that high spatial frequency targets such as high contrast letters are relatively insensitive to the effects of glare (Bailey and Bullimore 1991). The stimulus was presented for 250msec against a mean luminance background at the centre of a 24-inch Sony Trinitron color graphic display model GDM-FW900 running at 100Hz refresh rate. Baseline background luminance was 106cd/m$^2$ but this could be systematically reduced to measured values of 12.9, 1.68, 0.23

and 0.027cd/m$^2$ respectively via the addition of multiple layers of 0.9 log unit ND filter. The majority of the display was hidden by a circular mask providing a central hard-edged window of 3.2 degrees diameter at the viewing distance of 1.6 metres. Timing and contrast of the stimulus was controlled by a ViSaGe Visual Stimulus Generator (VSG2/5; Cambridge Research Systems, UK), allowing for 12-bit contrast resolution. The host computer was a Dell desktop PC.

The orientation of the presented Gabor patch could be oblique right or left, allowing for a two-alternative forced-choice response from the observer, using the right and left arrow keys of a conventional keyboard. Observer responses and stimulus control were overseen by custom-written software in MatLab (Mathworks, USA). Observer responses fed into a staircase routine controlled by a PEST algorithm centred on 84% correct response level. Initial step size was 4dB, falling to 2dB after the first reversal and 1dB after the second. The sequence terminated after four reversals. CS values occurring after the first reversal were averaged to produce a mean CS value along with a standard deviation. All data presented represent an average of at least two CS estimates.

CS was measured monocularly in both the right and left eyes, and in a binocular condition. All measurements were carried out in a darkened room. Measurements were taken in a baseline no-glare situation involving normal viewing and also in a with-glare situation during which observers wore a commercially-purchased HMD (Google Glass Explorer Edition 2.0). The characteristics of this display are outlined elsewhere (Hwang and Peli 2014), but briefly, the device was worn in accordance with the manufacturer’s advice such that the display was centred seven degrees of visual angle above the line of sight of the right eye when looking straight ahead. The device display contained a rectangular field (13° x 7.3°) (Hwang and Peli 2014) of approximately mean luminance, generated by taking a photograph of an illuminated white wall within the laboratory. When worn in this way, the Glass display appeared above the circular aperture of the monitor, on which the CS stimulus was presented, with no overlap of the two. Monocular measurements involved introducing a black opaque occluder, positioned between the Glass and the monitor. This ensured the HMD screen was still visible when the right eye was occluded.

Following a user-defined period (up to 1 minute) of inaction, the brightness of the Glass display automatically drops to a much lower level than in normal use. We measured the luminance of the HMD display as being 6cd/m$^2$ at this inactive level, rising to 80cd/m$^2$ in the active situation. Our CS measurements were taken in both inactive and active conditions, with the wearer giving the Google Glass frame a gentle tap every 60 seconds to restore the active status. The Glass incorporates an ambient luminance detector in order to control the display brightness under different light levels. This would have resulted in a gradual reduction in display brightness during our CS measurement routine. To prevent this, we used a small LED, invisible to the wearer, to maintain the display luminance at its maximum activated level. Our findings therefore represent a worst case scenario e.g. sudden screen activation or moving inside into a dark room on a bright sunny day where the display would take some time to react to the change in ambient luminance.

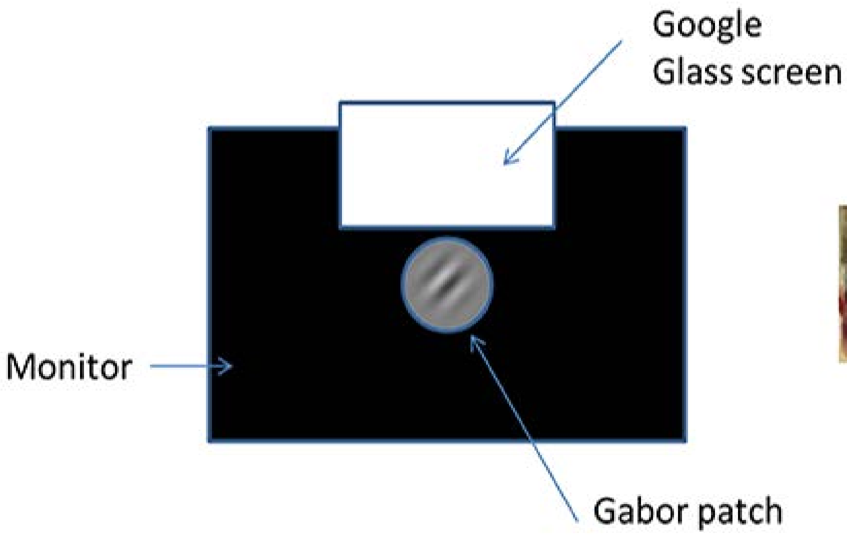


Figure 8.1 left shows the position of the Glass display in relation to the Gabor patch stimulus. Right shows the position of the Glass display in relation to the pupil.

### *8.2.1 Observers*

The two authors acted as observers. Both were male, aged 32 (CL) and 52 (DW) years. Both had normal VA (Snellen VA of at least 6/4). CL was emmetropic whilst DW was a moderate myope corrected for the 1.6m viewing distance by daily disposable single vision contact lenses. Natural pupil sizes were used throughout to correspond with normal viewing conditions when wearing the Glass device. Pupil sizes in each viewing condition were measured using a Tobii T60 XL Eye Tracker (Tobii, Stockholm, Sweden). This allowed retinal illuminance levels to be calculated from the relevant stimulus luminance conditions. Neither observer had any significant baseline anisocoria, nor was any significant anisocoria introduced by presenting the glare source to just one eye, indicating a full consensual pupil response. Mean interocular absolute pupil size differences were less than 0.07mm (CL) and 0.05mm (DW) and binocular retinal illuminance levels were therefore taken to be a mean of the two monocular levels. The tenets of the Declaration of Helsinki were observed and the experiments received institutional ethical approval.

## 8.3 Results

For both observers, CS in the two eyes is almost identical across all retinal illuminance levels, with the binocular condition showing an advantage over the monocular performance, as would be expected from binocular summation. CL's data suggest that the advantage of binocular viewing declines with reducing luminance, although this is less evident for DW. Averaged across luminance, the ratio between binocular contrast thresholds and the better of the two monocular thresholds is 1.30 ± 0.22 for CL and 1.44 ± 0.08 for DW, close to the value of √2, the widely accepted level of binocular summation (Campbell and Green 1965a; Blake et al. 1981; Legge and Rubin 1981). The Retinal illuminance can be calculated simply if the stimulus luminance and the pupil area are known:

$$T = L \times p$$

Where T is the retinal illuminance in trolands (Td), L is the stimulus luminance in cd/$m^2$ and p is the pupil area in $mm^2$.

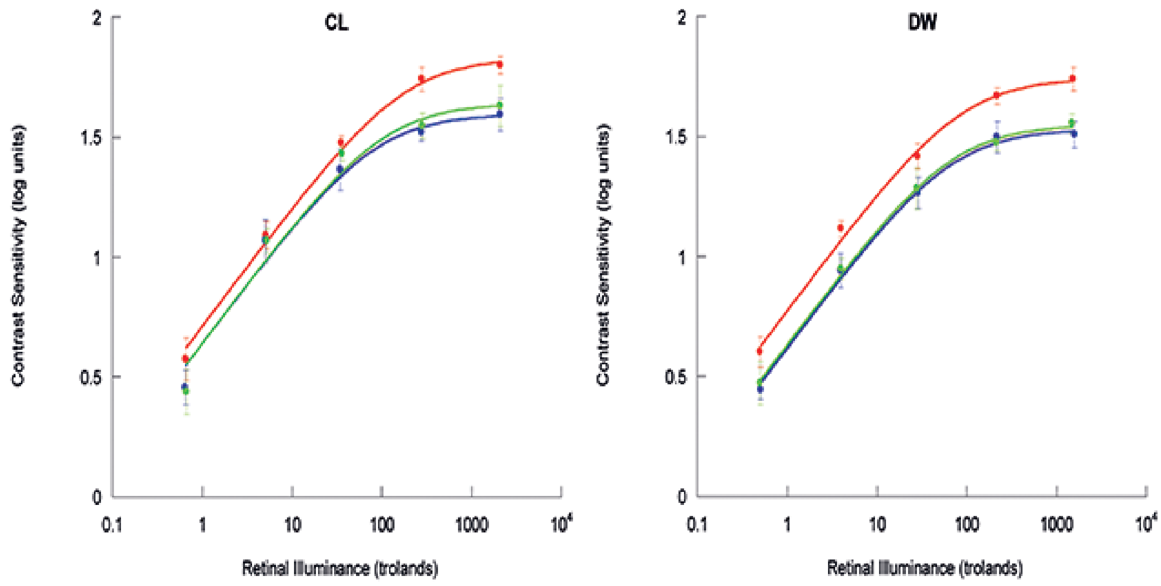


Figure 8.2 showing baseline CS values without the HMD. CS is shown as a function of retinal illuminance produced by the stimulus for both monocular conditions (left eye green, right eye blue) and for binocular (red) viewing.

The curves fitted to the data are those expected by taking into account the spectral densities of neural and quantal noise (Pelli 1990; Rovamo et al. 1994). It can be shown (Mustonen et al. 1993) that

$$logCS = \ logCS_{max} - 0.5 \times log\left(1 + \frac{E_c}{E}\right)$$

Equation 8.1

where $logCS_{max}$ is the optimum CS found at very high luminance levels, $E$ is the retinal illuminance produced by the stimulus (values along the abscissa) and $E_c$ is a constant representing the critical illuminance marking the transition between constant CS at high illuminance levels (Weber's law) and the descending portion of the function where CS falls with a gradient of 0.5 log units per log unit of retinal illuminance reduction (DeVries-Rose law) (De Vries 1943; Rose 1948). Equation 8.1 is simply the log transform of Equation 3 from a previous study

(Mustonen et al. 1993). It can be seen that this model (having just two, free parameters) does an excellent job of explaining the data, accounting for over 99% of the variance of the entire data set. The relevant parameters for the curve fits are shown in Table 8.1 – note how the binocular advantage in CS is reflected in a significantly higher $logCS_{max}$ in binocular viewing.

Table 8.1. Showing optimum CS ($logCS_{max}$), critical illuminance ($E_c$) (marking the transition between Weber's law and the DeVries-Rose law) and $R^2$ values for both participants, without glare.

| | $logCS_{max}$ (log units) | $E_c$ (trolands) | $R^2$ |
|---|---|---|---|
| CL Binocular | 1.830±0.034 | 169.3±35.8 | 0.996 |
| CL Right eye | 1.597±0.061 | 80.1±32.3 | 0.980 |
| CL Left eye | 1.642±0.077 | 98.3±49.3 | 0.973 |
| DW Binocular | 1.744±0.029 | 84.5±15.7 | 0.996 |
| DW Right eye | 1.533±0.024 | 65.3±10.4 | 0.997 |
| DW Left eye | 1.550±0.016 | 66.6±6.9 | 0.999 |

The data obtained when wearing the HMD are now given. First we present data for the right eye – the eye directly exposed to the glare.

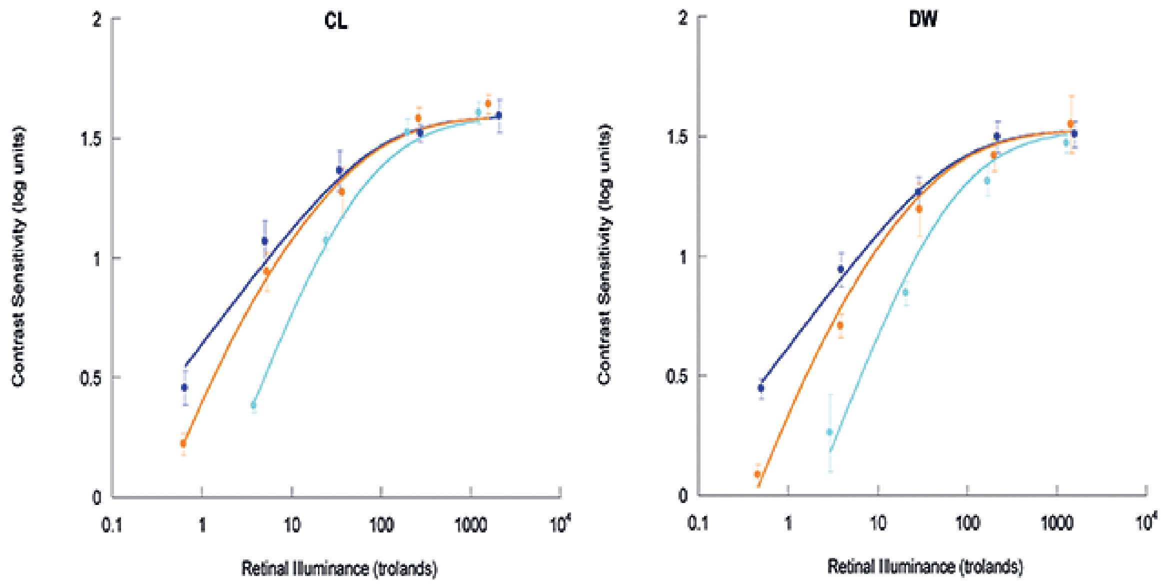


Figure 8.3 showing CS results for the right eye of both participants as a function of retinal illuminance produced by the stimulus. Baseline CS is shown by the blue line, CS in the inactive glare condition is shown by the orange line and CS in the active state is shown by the turquoise line.

The blue data are for the right eye in the absence of glare – this is the same data as for the right eye in Figure 8.2. The orange data represent CS in the presence of glare with the Glass device in its inactive state, whilst the turquoise data show the same for the device in its active state. CS is reduced in the presence of glare, particularly at low stimulus luminance, and for the active state in which the glare source is brighter. In order to model the data we expand Equation 8.1 to include a term representing DG. The main cause of DG is the veiling illuminance, arising from the glare source which is superimposed upon the retinal image of the stimulus, thereby reducing its contrast. Allowing for a conversion from physical stimulus luminance to the resultant retinal illuminance, a well-established formula for DG is

$$DG = log\left(1 + \frac{Ev}{E}\right)$$

Equation 8.2

which indicates that DG increases as the amount of veiling illuminance from the glare source (*$E_v$*) increases, and as retinal illuminance (*E*) decreases (Paulsson and Sjostrand 1980; Steen et al. 1993; Whitaker et al. 1994). Subtracting this from Equation 8.1, and accounting for the fact that veiling illuminance increases overall retinal illuminance, leads to the following expression:

$$logCS = \ logCS_{max} - 0.5 \times log\left(1 + \frac{E_c}{E + E_v}\right) - log\left(1 + \frac{E_v}{E}\right)$$

Equation 8.3

Equation 8.3 was fitted to the data for the glare conditions, carrying forward values for $logCS_{max}$ and $E_c$ from the original no glare condition from Figure 8.2 (red curve fit). Note that we have therefore added just one free parameter - the veiling illuminance $E_v$. The goodness-of-fit of the orange and turquoise curves show that this model accounts well for the with-glare data. Values for veiling illuminance and associated $R^2$ values are given in Table 8.2. Veiling illuminance is greatly increased when the Google Glass is in its active state. In addition, levels of veiling illuminance appear to be slightly higher for the older of the two observers.

Table 8.2. Veiling Illuminance $E_v$ and associated $R^2$ values from Figure 3 in both glare conditions.

| | $E_v$ (trolands) | $R^2$ |
|---|---|---|
| CL glare, inactive state‡ | 1.98±0.50 | 0.993 |
| CL glare, active state§ | 28.6±3.5 | 0.996 |
| DW glare, inactive state‡ | 2.54±0.72 | 0.990 |
| DW glare, active state§ | 37.7±8.2 | 0.980 |

‡ with Google Glass screen luminance at $6cd/m^2$, § with Google Glass screen luminance at $80cd/m^2$

The data obtained when wearing the HMD are now given for the LE, which itself received no direct glare. Figure 8.4 shows that a single function (Equation 8.1) accounts well for CS under both glare and no-glare conditions. Although the glare source produces a consensual pupil constriction in the left eye, plotting CS in terms of retinal illuminance accounts for this effect at least at the relatively low spatial frequency we have used (Campbell and Green 1965b; van Meeteren 1974).

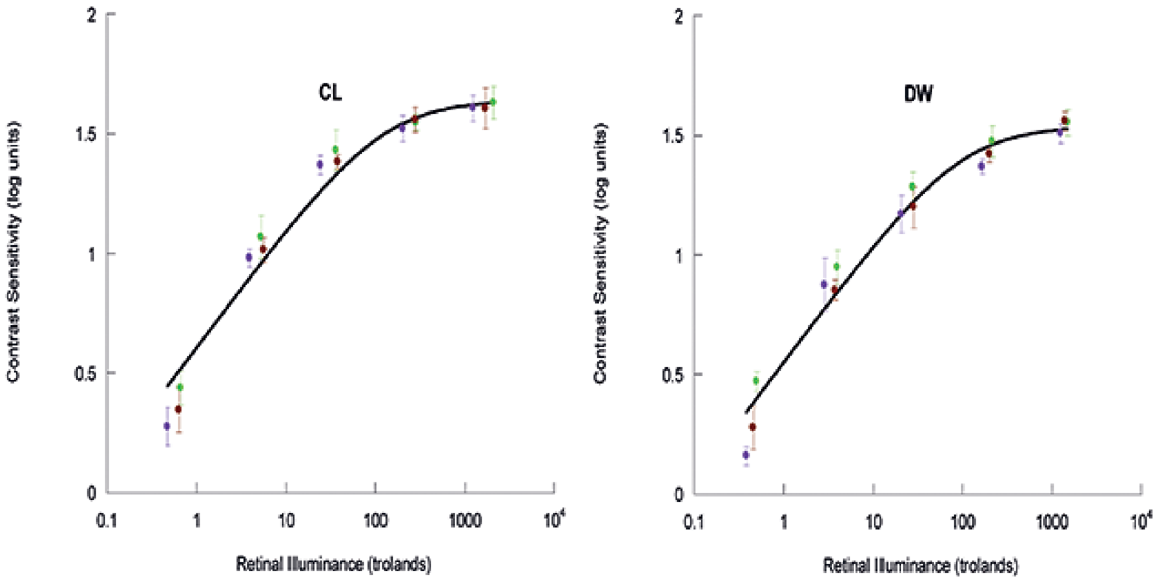


Figure 8.4 showing CS results for the left eye of both participants under the three glare conditions (green – no glare; maroon – inactive state; purple – active state). A single function (Equation 8.1) is fitted to the entire data set.

Table 8.3. Showing optimum CS ($logCS_{max}$), critical illuminance ($E_c$) and $R^2$ values for the left eye of both participants, for all glare conditions combined.

| | $logCS_{max}$ (log units) | $E_c$ (trolands) | $R^2$ |
|---|---|---|---|
| CL Left eye | 1.641±0.046 | 115.8±33.9 | 0.967 |
| DW Left eye | 1.539±0.041 | 93.3±24.1 | 0.972 |

Finally, the data is given whilst wearing the HMD in the high glare condition (active setting) to demonstrate the effect of the monocular glare source on binocular visual performance. Figure 8.5 shows data for the right and left eyes in this glare condition (taken from Figures 8.3 and 8.4 respectively) plotted alongside the equivalent binocular performance. This shows that, at high stimulus luminance levels, where performance in the right and left eyes is similar, binocular summation (better binocular performance than monocular) is very much evident. However, on moving to the left hand side of the Figures, as performance in the right eye deteriorates in comparison to the left, the advantage of binocular performance relative to the better monocular eye is lost. Importantly, though, we do not observe any sign of binocular inhibition, where binocular performance becomes poorer than the better monocular sensitivity.

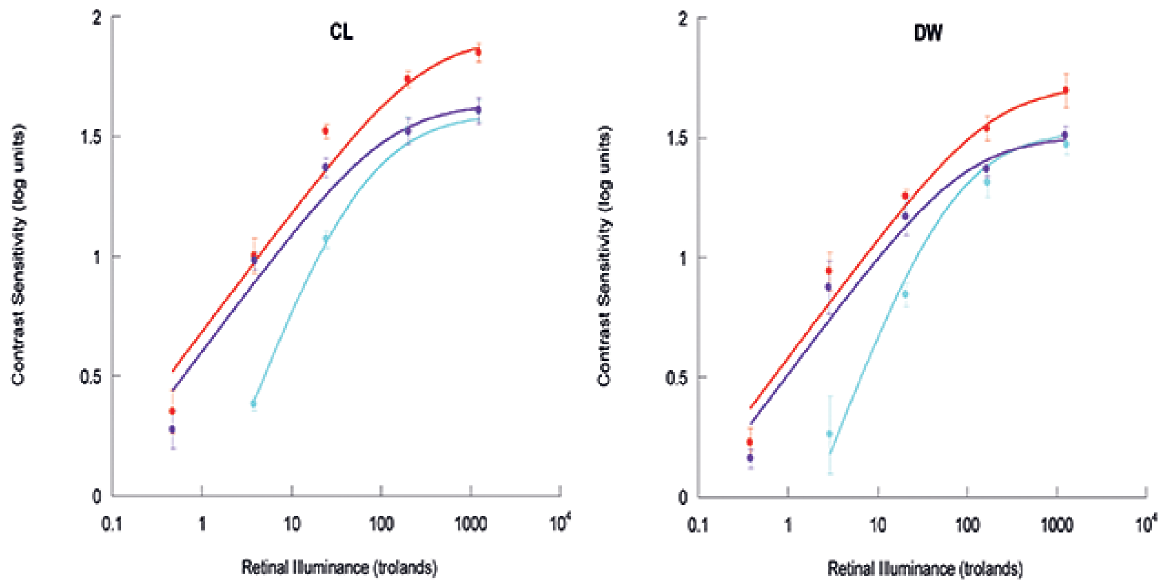


Figure 8.5 showing monocular and binocular CS results for both participants in the active state: Binocular (red), left eye (purple) and right eye (turquoise).

### 8.4 Discussion

The use of HMDs is predicted to become increasingly widespread over the coming years. Glass is only one device that has been developed for use in this area. Other commercially and previously available prototype devices have been described elsewhere (Vargas-Martin and Peli 2002; Brusie et al. 2015) and all could potentially have an impact on CS under conditions of low luminance. These devices all differ in display dimensions, brightness and position and are therefore likely to result in differing levels of DG during use. The method we have used for this study could be applied to other similar devices to measure the likely effect on visual performance in conditions of low lighting.

Here we have investigated one way in which a wearer's visual performance might be limited by such a device, demonstrating a significant reduction in monocular visual performance due to DG. Binocular visual performance of the wearer is also reduced, but to a modest extent due to the loss of binocular summation. Our data therefore contribute to the debate over the safety of such devices in various situations, including driving (Peli 1999; Sawyer et al. 2014; He et al. 2015). The reduction in CS in the presence of a glare source (DG) has been shown to hinder driving performance and have a detrimental impact on pedestrian recognition at night (Theeuwes et al. 2002; Wood et al. 2012). In bright conditions, such as daytime driving, our data show that the HMD display produces no reduction in visual performance in either eye, leaving normal binocular summation intact. In fact on a bright sunny day wearing an HMD could even improve visual performance, reducing foveal scatter by blocking some of the light from a very bright sky, which can measure over 20,000cd/m$^2$ in certain conditions (Perez et al. 1990). It is only when stimulus luminance is reduced that very significant levels of DG are found, with the implication that such devices are inappropriate to use for night time driving. The age of the wearer also needs to be considered, since DG increases markedly in the elderly, even in the absence of overt media opacities (Vos 2003a; van den Berg et al. 2007; van den Berg et al. 2009b).

Additional caution needs to be taken in wearers without normal binocular vision, for example in those who have amblyopia or monocular cataract or other pathology. If the visual display is worn, as is likely, in front of the dominant eye, the wearer no longer has the fellow eye to rely upon when the good eye is exposed to significant levels of DG. In these conditions, binocular visual performance may well be dramatically reduced by monocular glare from the HMD.

Whilst we found a loss of binocular summation under glare conditions, we did not observe any binocular inhibition which might have been expected from previous studies (Fechner 1860; Pardhan and Gilchrist 1990a; Pardhan and Elliott 1991). This is unlikely to have been due to our choice of stimulus (a single spatial frequency of 1.7 cycles per degree) since binocular inhibition has been found to be independent of spatial frequency (Pardhan et al. 1989). It may be that we were unable to produce sufficient levels of DG in the right eye to demonstrate the effect, and it is possible that an increased DG effect, either through a brighter display luminance or an increase in the age of the wearer, would have given rise to some binocular inhibition.

It is important to note that the device in question is currently in a re-design phase and no longer commercially available. A new version of Glass is due to be released in the near future and it will be interesting to see whether any changes to the display geometry or size, display luminance, or its proximity to fixation might affect the magnitude of DG effects we have reported here.

Visual performance in HMD wear is likely to become an increasingly important issue as the use of these devices rises and as the average age of the wearers increase. The present work has quantified just one aspect of visual performance reduction (DG) in normal vision. Clearly there is more to be done in establishing where, when and how such devices should be used to ensure the safety of the wearer and those around them.

# 9.0 Disability glare produced by a typical satellite navigation system

## 9.1 Introduction

The initial designs for satellite navigation (SatNav) technology were first approved by the US Military in 1973. The system was declared fully operational in 1995 (Enge and Misra 1999) but commercial use of these systems did not start to take off until the early 2000's (Lendino 2012). Since then they have become the norm for many drivers in establishing the best route to reach a desired destination. In 2014 52% of UK drivers were using either integrated or dash-mounted SatNav systems (Department for Transport 2014). They use positional data and previously downloaded map information to produce a set of visual and audio cues, providing turn by turn information to the driver of the vehicle (Brown and Laurier 2012). They offer active updates for unforeseen route changes, negating the need for route memorization and/or the requirement to stop and consult a map. Driver behaviour and car handling has been shown to improve whilst using SatNav equipment when compared to the use of ordinary maps (Lee and Cheng 2008).

SatNav systems have however also been shown to have their issues. Poorly designed systems may lead to distraction if instructions are presented to the driver in an incoherent manner (Beattie et al. 2015). In particular, driver safety could be put at risk when information is presented which does not directly correspond to the intentions of the person behind the wheel (Hipp et al. 2010). The small size of SatNav displays can exacerbate driver distraction and therefore impact on driver safety (Brown and Laurier 2012). Driver distraction can lead to driving errors including improper speed and directional movements (Kun et al. 2009).

Despite the widespread use of SatNav systems there does not appear to be any literature discussing how visual function is affected by their use. Although easily managed, if a SatNav device was poorly positioned it could produce a scotoma in the visual field of the driver. During the daytime other effects on visual function would likely be minimal. At night the display screen of such a device, other than the effects already mentioned, may also turn into a glare source affecting the driver's vision. DG has already been discussed extensively in this thesis, but briefly, it describes light that is scattered by the ocular media, producing a veiling luminance across the retina and reducing the contrast of the retinal image (Allen and Vos 1967; Vos 1984; Vos 2003a; van den Berg et al. 2009b; van den Berg et al. 2013).

The DG produced by these devices would be of low clinical significance during the day as target luminance (object being viewed) would be much higher than the luminance of the SatNav. At night the situation would likely be reversed where the luminance of the SatNav could be much higher than the luminance of the target (e.g. a pedestrian at the side of the road). Therefore the effects of DG would be much higher and visual function could be seriously affected, especially in those with cataract (Elliott and Bullimore 1993; van Rijn et al. 2005; Babizhayev et al. 2009; van den Berg et al. 2009b). The amount of DG these systems produce in both the normal and cataract populations would therefore appear to be of vital importance when considering driver safety.

## 9.2 Methods

Four observers, 2 male (observer 1 aged 32, observer 2 aged 52) and 2 female (observer 3 aged 29, observer 4 aged 24) participated in the data collection procedure. All observers had normal VA (Snellen VA 6/4). Observers 1 and 3 were emmetropic and observers 2 and 4 were moderate myopes corrected for the 1.6m viewing distance by using daily disposable, single vision, contact lenses. Natural pupil sizes were used throughout to correspond to the natural conditions of SatNav usage. The tenets of the declaration of Helsinki were observed and institutional ethical approval was granted.

CS levels were measured as described previously where the stimulus (Gabor patch) was presented for 250msec at the centre of a 24 inch Sony Trinitron color graphic display model GDM-FW900 running at 100Hz refresh rate against a mean luminance background (Longley and Whitaker 2015). Stimulus presentation and observer responses were looked after by custom-written software in Matlab (Mathworks, USA). Baseline background luminance levels were systematically reduced with the addition of 1, 2, 3 and 4 layers of a 0.9 log unit neutral density filter. A relatively low spatial frequency target was used as high spatial frequency targets have been shown to be largely insensitive to the effects of glare (Bailey and Bullimore 1991). Lower spatial frequencies also appear to be more important for vehicle navigation (Owsley et al. 2001).

CS measures were recorded in a darkened room at 5 different luminance levels, altered using the aforementioned neutral density filters. At each of these luminance levels CS was measured in four different situations. The first condition was a baseline measure, in the second CS was recorded with the

SatNav system activated, the third condition involved the measurement of CS with a cataract simulator in place and the final condition measured CS using the cataract simulator with the SatNav system activated. The order of the conditions tested was randomized for each participant. Participants were given enough time to fully recover from any glare after-effects between measurements. Mean CS and standard deviation of the deviations were recorded for all participants in every condition. As the cataract simulator was monocular in its design all measurements were taken using the right eye of each participant. The fellow eye was covered using a black opaque occluder.

The SatNav device used for data collection during this study was the commercially available TomTom Via 135 M 5” SatNav (TomTom NV, The Netherlands). This was positioned approximately 70cm away from the participant, 20° to the left and 20° below fixation in an attempt to closely mimic the position of a SatNav whilst driving. Most SatNav devices incorporate a light sensor into their design which dims the luminance of the display screen when the ambient light level falls. Other integrated systems automatically dim when the car headlights are activated. Both measures are designed to reduce any glare effects which may be caused by these systems. However, SatNav devices also have manual settings which allow screen brightness to be turned to a maximum and the device night-mode to be deactivated. Even when the device used during this study is in its night condition, if the settings screen is subsequently activated the screen luminance rises dramatically. For this reason the data collected during this study was recorded when the SatNav device was set to its main options screen, where average screen luminance was measured at 230cd/m$^2$ by direct photometry (Minolta chroma meter CS-100, Japan). This study therefore represents a worst case scenario where screen luminance is high, but it does represent a scenario that a driver could easily experience.

The cataract simulator used for this study was produced specifically for purpose; similar to a design published previously (Steen et al. 1993). This incorporated the use of two 70mm plano lens blanks, separated using a 1cm wide plastic charity bracelet, affixed using extra strong waterproof glue. In order to obtain an accurate volume measure for the lens system 50ml of de-ionized water was added to a beaker, then using a pipette the lens system was filled. The amount of water left over gave an accurate value for the volume of the lens system. For the cataract simulator itself 1 drop of 500nm monodispersed polystyrene microspheres (Polysciences Inc., Warrington, USA) was added to the lens system and the remainder filled with de-ionized water and then sealed. This produced a 0.08% concentration of the microsphere suspension and resulted in the simulation of mild nuclear cataract. VA of participants was largely unaffected with the cataract simulator in place.

Figure 9.1 showing the lens system used to produce the cataract simulator.

## 9.3 Results

The data for all participants under all conditions were plotted and curves fitted, taking into account the spectral densities of neural and quantal noise (Pelli 1990; Rovamo et al. 1994). It can be shown (Mustonen et al. 1993) that

$$logCS = \ logCS_{max} - 0.5 \times log\left(1 + \frac{L_c}{L_s}\right)$$

Equation 9.1

where *$logCS_{max}$* is the maximum CS found at very high luminance levels, $L_s$ is the luminance of the stimulus and $L_c$ marks the critical luminance where there is a transition between Weber's law (constant CS at high luminance levels) and the De Vries-Rose law (De Vries 1943; Rose 1948) where CS falls with a gradient 0.5 log units per log unit reduction in stimulus luminance.

During this study a commercially available SatNav system was employed in order to examine the amount of DG produced by such a device. In order to model the data recorded while the SatNav was operational an additional term representing DG needed to be added to equation 9.1. The term used for this purpose was the well-established equation for DG (Steen et al. 1993; Longley and Whitaker 2015).

$$DG = log\left(1 + \frac{L_v}{L_s}\right)$$

Equation 9.2

this expression shows that as the veiling luminance *($L_v$)* produced by the glare source increases and the stimulus luminance *($L_s$)* decreases the amount of DG increases (Paulsson and Sjostrand 1980; Whitaker et al. 1994). An increase in $L_v$ not only increases the amount of DG but it also contributes to the amount of retinal illuminance produced by the stimulus. Taking this into account, the expression for CS minus the amount of DG produced by the glare source can be written as:

$$logCS = logCS_{max} - 0.5 \times log\left(1 + \frac{L_c}{L_s + L_v}\right) - log\left(1 + \frac{L_v}{L_s}\right)$$

Equation 9.3

Equation 9.3 was therefore used to fit the data recorded with the SatNav activated. The values of $logCS_{max}$ and $L_c$ that were calculated from the original no glare condition were used, meaning the expression had just one free parameter $L_v$.

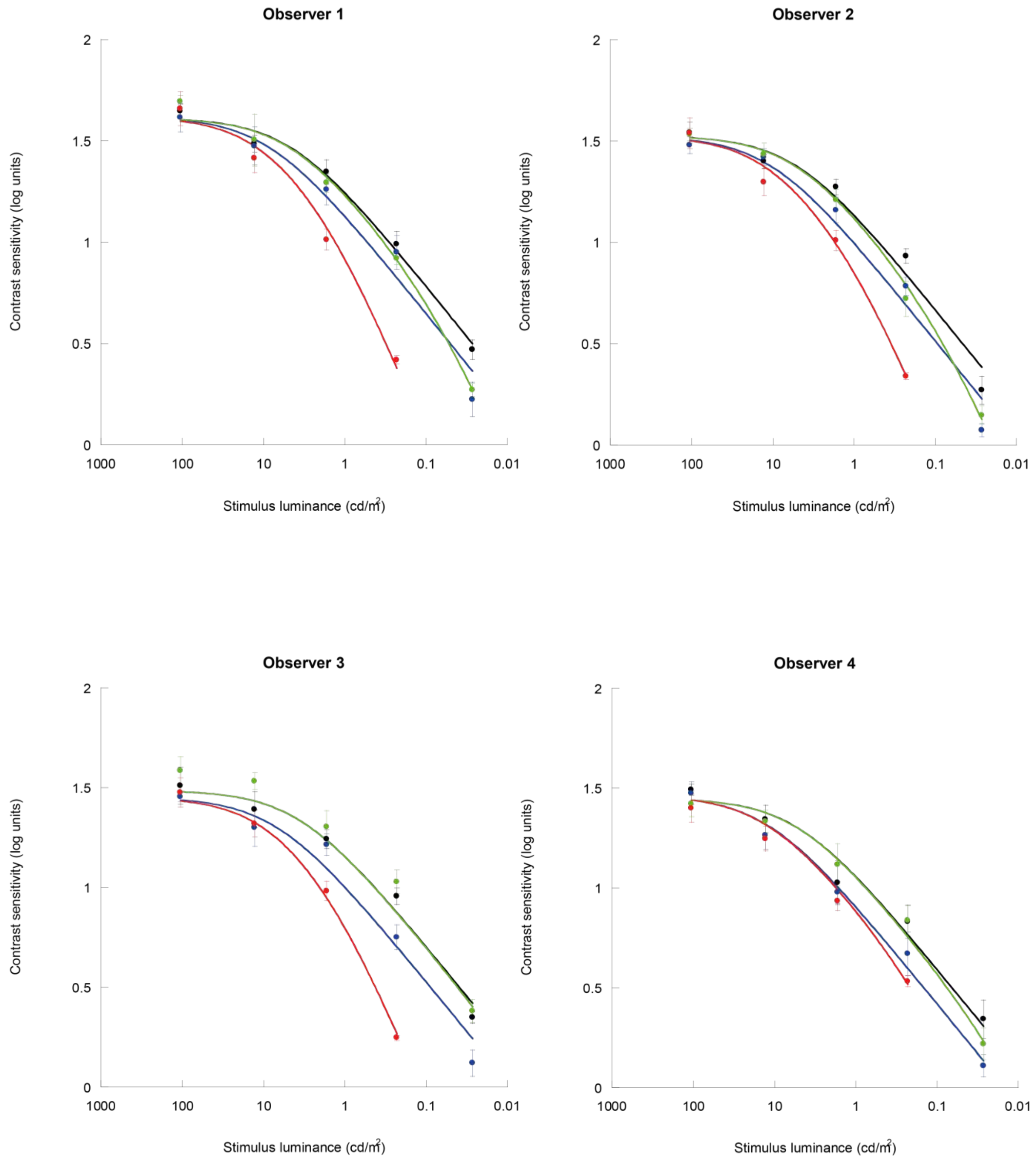


Figure 9.2 showing the CS achieved by each participant in each of the four conditions previously mentioned. The black line represents baseline CS, the green line indicates the CS with the SatNav activated, the blue line represents the CS achieved with the cataract simulator in place and the red line shows the data recorded with the simulator in place and the SatNav activated.

Figure 9.2 above shows the performance of all participants under all conditions. The black line represents baseline CS, the blue line shows the CS acieved with the cataract simulator in place, the green line shows the performance when the SatNav was activated and lastly the red line indicates how CS was impaired when both the SatNav was activated and the cataract simulator was in position. The plotted data for each of the participants is very similar. Baseline CS is shown to be almost identical to the performance when the SatNav is activated. The SatNav only appears to start affecting CS at very low luminance levels where performance just dips below baseline level at the right hand side of each plot.

In all particpants, the blue line representing the CS recorded when the cataract simulator was in position, is consistently poorer than baseline performance at all but the highest luminance levels. Optimum CS levels for both baseline and simulator conditions are very similar for each participant, shown by the $logCS_{max}$ values listed in table 9.1. However CS level starts to decline earlier in the simulator condition, shown by the higher critical luminance values $L_c$. The data shows a consistent doubling of $L_c$ values for all participants between baseline and simulator conditions. The model used does an excellent job of explaining the data, accounting for approximately 99% of the variance of the whole data set for all participants.

Table 9.1. Showing optimum CS ($logCS_{max}$), critical luminance ($L_c$) (marking the transition between Weber's law and the De Vries-Rose law) and $R^2$ values for all participants. These results were calculated using equation 9.1 and therefore without the SatNav in place.

| | $logCS_{max}$ (log units) | $L_c$ (cd/m$^2$) | $R^2$ |
|---|---|---|---|
| Obs 1 Baseline | 1.62±0.04 | 4.5±1.3 | 0.995 |
| Obs 1 Simulator | 1.62±0.11 | 8.7±5.6 | 0.984 |
| Obs 2 Baseline | 1.53±0.08 | 5.2±2.7 | 0.987 |
| Obs 2 Simulator | 1.53±0.11 | 10.6±7.0 | 0.986 |
| Obs 3 Baseline | 1.49±0.06 | 3.6±1.4 | 0.991 |
| Obs 3 Simulator | 1.45±0.10 | 7.0±4.3 | 0.985 |
| Obs 4 Baseline | 1.45±0.08 | 5.2±2.5 | 0.986 |
| Obs 4 Simulator | 1.47±0.06 | 12.3±4.5 | 0.995 |

The final condition where the SatNav system was activated and the cataract simulator was held in place, is shown by the red line on the plots in figure 9.2. Observers 1, 2 and 3 show a significantly reduced CS especially at lower luminance levels in this condition when compared to baseline performance. This drop in CS was expected as cataract is well known to increase the amounts of light scatter in the eye and have a detrimental effect on visual function (van Rijn et al. 2005; van den Berg et al. 2009b). The performance of observer 4 in this condition seems to be less seriously affected. Only at the very lowest luminance levels does performance start to decline. Veiling luminance $L_v$ values shown in table 9.2 are significantly higher for each participant when the simulator was in position.

Table 9.2. Veiling luminance $L_v$ and associated $R^2$ values from the glare involved conditions in figure 9.1.

| | $L_v$ (cd/m$^2$) | $R^2$ |
|---|---|---|
| Obs 1 SatNav | 0.049±0.017 | 0.996 |
| Obs 1 SatNav +Sim | 1.337±0.345 | 0.993 |
| Obs 2 SatNav | 0.060±0.014 | 0.998 |
| Obs 2 SatNav +Sim | 0.840±0.205 | 0.995 |
| Obs 3 SatNav | 0.002±0.015 | 0.974 |
| Obs 3 SatNav +Sim | 1.231±0.170 | 0.998 |
| Obs 4 SatNav | 0.011±0.009 | 0.995 |
| Obs 4 SatNav+Sim | 0.099±0.084 | 0.988 |

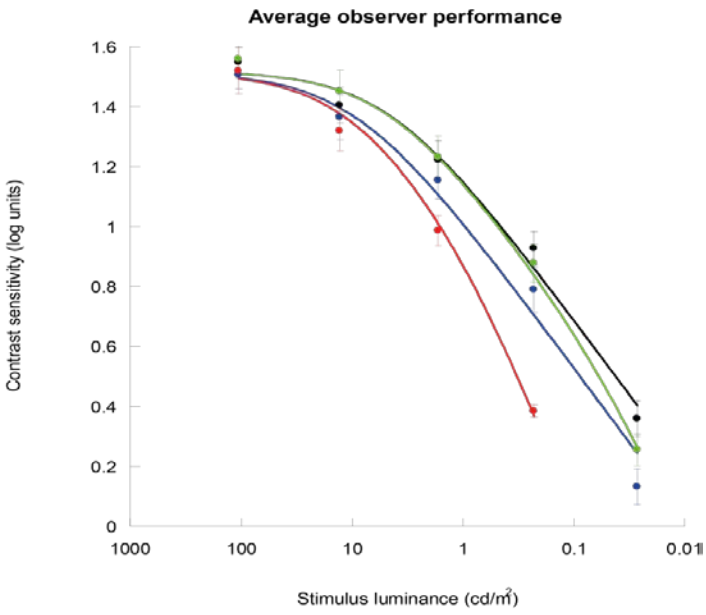


Figure 9.3 showing the average observer performance for the four conditions at the different luminance levels used. Once again baseline performance is represented by the black line, CS recorded with the cataract simulator is shown by the blue line, the green line represents performance with the SatNav activated and the red line shows the CS when the SatNav was activated and the cataract simulator was in place.

Figure 9.3 and table 9.3 show the average observer performance from each experimental condition. Compared to baseline performance CS was significantly impaired when the cataract simulator was used in conjunction with the SatNav device, particularly at lower luminance levels. The SatNav itself also begins to have an effect on CS at the lowest luminance levels measured, but to a much more minor extent.

Table 9.3. Showing the average values from the four participants for optimum CS *(logCS$_{max}$)* and the critical luminance *($L_c$)* without the SatNav as a glare source. The values for the amount of veiling luminance *($L_v$)* with the SatNav activated and the associated $R^2$ values from each model are also presented.

| | *LogCS$_{max}$*(log units) | $L_c$(cd/m$^2$) | $L_v$(cd/m$^2$) | $R^2$ |
|---|---|---|---|---|
| Baseline | 1.52±0.05 | 4.6±1.5 | | 0.994 |
| Simulator | 1.52±0.08 | 9.4±4.7 | | 0.990 |
| SatNav | | | 0.02±0.01 | 0.998 |
| SatNav +Simulator | | | 0.77±0.15 | 0.997 |

## 9.4 Discussion

The results presented above show that even mild lens changes can produce a significant decline in CS at lower luminance levels when a SatNav device is in use. When the ocular media is clear the device affects CS levels at the very lowest luminance levels but to a much more minor extent. As SatNav devices contain model and manufacturer differences the results cannot be generally extended to every commercially available device. However the methods do present a technique that could be used to investigate how much glare current and future devices produce. Screen size, brightness and position are factors which would all likely alter the amounts of DG.

Older individuals have previously been shown to have reduced CS at all light levels, however this reduction is particularly significant at lower luminances (Sloane et al. 1988). They also require a higher contrast to perceive real world targets such as road signs (Owsley and Sloane 1987) and faces (Owsley et al. 1981). Cataract has also been shown to further impair CS when compared to age-matched, normal participants (Elliott and Situ 1998) and produce greater amounts of intraocular light scatter when a glare source is present (van den

Berg et al. 2009b). This increase in light scatter produces a greater amount of DG further reducing CS (Elliott and Bullimore 1993; Pesudovs 2007). The results generated with the cataract simulator in place and the SatNav activated are therefore not unexpected. However they do highlight a previously undiscussed issue where a SatNav device could seriously impair CS especially at the luminance levels found when driving at night. Well illuminated urban roads have been shown to have a luminance anywhere between 0.76 and 5 $cd/m^2$ depending on conditions (Ekrias et al. 2007). At these luminance levels the SatNav would have a modest effect on CS, even when early cataractous changes are present. However, the luminance of un-lit country roads has been measured to be as low as $0.06cd/m^2$ (Chauhan and Charman 1993) a luminance level where the SatNav causes a significant drop in CS in those with early cataract. In order to reduce the impact of glare from these devices users should be made aware of the consequences of manually altering screen brightness and accessing device settings whilst driving especially when driving on un-lit country roads.

The cataract simulator used during this study mimicked the effects of early cataract, where VA was largely unaffected by the opacity. The VA of observer 1 was reduced by 1 line (6/3 to 6/4) with the simulator in place. When the simulator was used a consistent rise in $L_c$ was observed for each participant when compared to baseline measures. The simulator will have had the effect of reducing the retinal illumination of the target (Elliott et al. 1996), which may result in the earlier transition between laws as the stimulus luminance was reduced. A similar lens system incorporating the same polystyrene microsphere solution was previously used to measure CS with the BAT. The whole measurement technique was shown to be a repeatable measure (Steen et al. 1993). The simulator, when used with the SatNav activated, produced a similar effect on 3 of the 4 participants tested. The 4th seemed mostly unaffected by the glare source in this condition. It is not altogether clear why this was the case. The participant who was least affected was the youngest of the four tested. Intraocular light scatter has been shown to increase with age (van den Berg et al. 2009b) and therefore this may go some way to explain this finding. However, the cataract simulator would have produced the vast amount of the veiling luminance in this condition and therefore its effects on CS would be expected to be very similar on all participants.

One of the main limitations found in this study was the use of stimulus luminance rather than retinal luminance for the data analysis. The models used to fit the data were intended to be used with retinal illuminance values (Mustonen et al. 1993; Rovamo et al. 1994) but at the time of data collection, pupil size measurements were not recorded. During the Google Glass study that was discussed in chapter 8, results were initially calculated using stimulus luminance and then secondly, using retinal illuminance. The plots obtained from both scenarios were very similar and therefore in a situation where a glare source was shown to produce a large deficit in CS, results can be used without the fear of reaching the wrong conclusion. If exact values of $L_c$ and $logCS_{max}$ were required in order to directly compare values for each participant, retinal illuminance values would be required. In this study where general effects of a device were analyzed, stimulus luminance values provide results accurate enough for purpose.

The cataract simulator did a good job at replicating the mild hazing in early nuclear cataract and substantially increased the amount of veiling luminance experienced by all of the participants used. It is a system that could be implemented in future studies, replicating different amounts of nuclear cataract. One main problem associated with the lens system was evaporation. It was not possible to make the system fully air tight and therefore evaporation occurred over time. For studies that take place short time periods (< 1 month) the same simulator could be used to collect data. However for data collection over longer periods of time the solution used to fill the lens system would need to be replenished, if this was not the case then the microsphere solution would continue to gain in concentration and therefore likely impact on the results recorded.

In summary, the older population with early lens changes could easily have CS significantly affected by a SatNav device used under the same conditions as found in this study. Manufacturers should therefore warn consumers over the risks involved with altering night-mode luminance levels or accessing the settings screen whilst driving. It may also be prudent to make recommendations regarding device positioning, although this would likely become a compromise between the amount of DG produced and the distraction effect of having to look further from normal fixation.

SatNav systems are widely used and will continue to be for the foreseeable future. The aforementioned recommendations and warnings should come with these devices in order to make our roads as safe as they can possibly be.

# 10.0 Conclusions and future work

## 10.1 The contrast sensitivity clock

In chapters 6 and 7 the CSC was shown to be a valid (measures what it is designed to measure), discriminative (provides clinical useful information in order to aid diagnosis) and repeatable test (repeatable results from the same person under identical measurement conditions), the three measures a glare testing device should be judged on in assessment of clinical performance (Elliott and Bullimore 1993).

Validity was assessed by way of correlations with questionnaire responses of perceived night driving difficulty. The correlations found with the CSC scores were similar to correlations seen with other commercially available devices.

The ability of the CSC to provide clinically useful diagnostic information was examined with the use of an ROC analysis. The discriminative ability of the CSC, in particular the CSCG scores were again found to be similar to other more established devices at distinguishing between cataract and normal participants. During the main CSC study in chapter 6, a ROC analysis using data from a new group of participants termed the “positive” group was analysed. The “positive” group contained participants who had cataract or other ocular pathology that may have led to impaired visual performance. Using the data obtained from this analysis a pass/fail level (CSCG score ≤ 0.75 log units) was recommended, keeping the number of false positive results to a minimum while identifying a sensible proportion of those most affected by DG. It is of utmost importance to keep the number of false positive results to a minimum in a study of this nature, where the consequences of failing the test could lead to social isolation and depression (Fonda et al. 2001) and reduce health-related quality of life (DeCarlo et al. 2003).

The repeatability of the CSC was assessed in chapter 7 in a direct comparison with the PR chart using the BAT as a glare source. The RC of the CSCG scores held up well against other devices and was of a similar level (2 step sizes) to that of the Pelli-Robson chart used in conjunction with the BAT. When the 95% confidence limits for change were calculated, the repeatability of the CSC scores was shown to be inferior to that of the PR chart scores. One obvious way to improve device repeatability would be to reduce the step size the CSC implements.  For example if the step size was reduced to 0.10 log units the minimum score from the CSC would equate to approximately 0.40 log units. Very few participants scored less than this value (n=2) and would therefore be an appropriate way in which to change the clock. Despite this, the current version of the CSC would appear repeatable enough for purpose. The average CSCG value of a normal participant was a substantial distance away from the pass/fail level previously discussed. This would lead to few false positive results and would therefore indicate the CSCG scores to be repeatable enough for purpose (van den Berg et al. 2009b).

## 10.2 Limitations of the study

Power calculations should have been examined in order to calculate the sample size required for parts of this study. After the initial data had been collected from the original version of the CSC the sample size required could have been calculated. One issue with this during the study was the amount of data recorded. If sample size calculations had been used then the participant sample would only have been correct for one measure. The fact that different participant groups were used and different measurement scores were recorded would have complicated any sample size calculation. In hindsight it may have been appropriate to calculate required sample size needed to effectively report how well CSCG scores discriminated between cataract and no cataract groups, the measures used most commonly in this study.

It is possible that the sample size used during the repeatability study could have provided mis-leading information. Although the participant sample used was similar in size and makeup to previous studies investigating the repeatability of similar devices, smaller sample sizes run the risk of finding acceptable levels of agreement between measures when a larger sample size would prove otherwise (McAlinden et al. 2011b). Sample sizes of at least 100 participants have been recommended for such studies (McAlinden et al. 2011b). Therefore it may have been more appropriate to use more participants in the repeatability study.

The questionnaire used to test device validity in this study was not appropriate. The questionnaire was chosen mainly because of its performance in studies involving pre and post-op cataract patients. A questionnaire specifically designed for the purpose would have been more appropriate. Although developed after the completion of this study the vision and night driving questionnaire (VND-Q) (Kimlin et al. 2016), would likely have been much more appropriate for purpose. Another option may have been to use a more objective measurement or “gold standard” in which to assess device validity however no such universally accepted device exists. A couple of earlier studies have used the CSLM as such a device (Elliott and Bullimore 1993; van Rijn et al. 2005), although during repeatability evaluation successive measures have been shown to be related, making the device prone to bias if the patient is allowed to control luminance change themselves (van Rijn et al. 2005). The updated instrument, the C-Quant (NSLM), has the advantage that the patient does not control luminance change, it uses a forced-choice psychophysical method and allows measurement of binocular straylight.

During the main part of this study a convenience sample of participants were used, many coming in for a routine sight test. As such it was not possible to dilate participants. LOCS III classification was designed for cataract assessment using a dilated pupil (Chylack et al. 1993b). This is because certain types of cataract, particularly cortical opacities, initially appear in the peripheral lens and therefore can be easily missed if mydriasis is not used. Although this will not affect results shown in this current study as all participants were tested using the same procedure, it is not possible to directly compare results to other studies were pupil dilation has been used (van den Berg et al. 2007).

### 10.3 Future Developments to the CSC

The printing method used to produce the CSC would need to be considered before the device could be commercially produced. After experimentation with all the print options available at the University, the method discussed in chapter 6 and further discussed in the chapter 7 was considered the best option available. This method produces a device suitable for laboratory work; however the need for re-calibration when re-printing the CSC after a period of inactivity would be unsuitable for commercial production. Therefore if the CSC were to become commercially available new print options would need to be investigated.

Elliott and Bullimore (1993) supported the suggestions of a report by the American Academy of Ophthalmology (AAO) that any clinical test should incorporate the following features:

The test should be a forced-choice psychophysical method.

Test targets should follow a uniform logarithmic progression.

Several trials should be used at each level of acuity or contrast.

The CSC, in its current design incorporates two of these features but fails to use several trials at each contrast level. During this study data has been collected enabling an appropriate cut off or pass/fail level CSCG score to be established. Therefore one obvious change to the CSC design would be to concentrate on CS levels around this pass/fail level. This would allow presentation of several trials at each contrast level, likely improving discriminative ability and as was the case with the PR chart when letter by letter scoring was introduced, its repeatability (Elliott et al. 1991a). A further comparison study involving a superior measure of device validity and one or more of the most widely used glare tests would then be indicated, using a larger participant sample for assessment of repeatability.

As was described in chapter 6 the CSC glare condition uses an annulus of letters mounted on a rectangular light box. This means that each letter is not surrounded by an equal area of the glare source. It is not expected that this would have any effect on the performance of the CSC, however a study is likely warranted investigating whether any particular position on the CSC would make a letter more easily identifiable.

After these changes are implemented and studies undertaken, it is hoped more concrete conclusions could be drawn regarding the performance of the CSC. Recommendations could hopefully then be made regarding the devices merits for driving standards assessment. Following on from this the usefulness of the CSC with pre and post-op cataract patients could also be evaluated.

### 10.4 Head-mounted display and SatNav systems

During this study a head-mounted display called Google Glass (Google Inc.), probably the best known device of this nature, was used to assess whether the display screen would cause a significant DG effect. In chapter 8 the Google Glass device was shown to produce significant glare reduced CS in the eye directly exposed to the display screen, particularly at low luminance levels. Similar effects were seen with the SatNav system used in chapter 9. CS was again significantly reduced by the display screen, particularly at low luminance levels if early cataractous lens changes were present. The effects of glare reduced CS should therefore be considered in the suitability assessment of any device to be used in low luminance situations like those seen whilst driving at night. The methods used in chapters 8 and 9 could be replicated to investigate the amount of DG produced by any such device.

The most interesting finding from the Google Glass study was the reduction in the levels of binocular summation at low luminance levels, where the monocular performance of the two eyes showed the greatest disparity. Previous studies have even shown binocular inhibition, where binocular performance falls to a level below that of the better monocular eye. This effect has been observed in instances of monocular cataract (Pardhan and Elliott 1991), monocular defocus (Pardhan and Gilchrist 1990b), unequal monocular illuminance (Fechner 1860; Gilchrist and Pardhan 1987) and monocular glare disability (Pardhan and Gilchrist 1990a). In chapter 8 no sign of binocular inhibition was observed. It is likely the difference in visual performance caused by the display screen did not produce enough of a disparity to cause this effect. Binocular summation was seen at all luminance levels tested with the Google Glass device; however the amount of summation was much reduced where the difference in performance between the two eyes was most pronounced. This study, along with the others mentioned above would therefore seem to promote the assessment of binocular rather than monocular visual performance (Pardhan and Gilchrist 1991; Azen et al. 2002; Chew et al. 2012) when evaluating an individual's ability to undertake any task which is normally done under binocular viewing.

### 10.5 Applications and computer implemented tests

The use of computer implemented technology including the introduction of applications (apps) for smart phones and tablets has increased substantially over the last 10 years. The huge increase in the use of these systems has led to some traditional paper-based measures of visual function to be implemented using computer based programmes and apps. VA measures using computerized and tablet devices have been shown to be directly comparable to measures taken from paper based tests (Ehrmann et al. 2009; Black et al. 2013). However CS measurement appears to be less straightforward. Computer based CS tests, displayed using LCD technology have consistently been shown to be less repeatable and show differences in the CS levels recorded when compared to PR chart measurement (Thayaparan et al. 2007; Kingsnorth et al. 2016). LCD screens used in tablet computers have lower contrast resolution available for image production when compared to CRT monitors (Kingsnorth et al. 2016). Despite this there are techniques available that are designed to improve the contrast of images shown on an LCD screen (Tyler et al. 1992). These have enabled contrast gratings to be displayed on mobile tablet devices which are reportedly indistinguishable from CRT monitor displays (Dorr et al. 2013).

Presently the maximum brightness that a tablet or display screen can produce is typically around 300cd/m$^2$. If this was used as a glare source, room illumination would need to be low. This would both prolong the duration of the test due to the need for dark adaptation and make countrywide standardization of the testing conditions difficult. For these reasons the suitability of an app based CSC would appear to be limited at this time, however the additional speed and flexibility these devices and applications allow will likely promote use in the years to come.

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# Appendices

There is one published journal article from the PhD thesis entitled:

**Google Glass Glare: disability glare produced by a head-mounted visual display**

This article carries the following reference:

Longley, C. and Whitaker, D. (2015) Google glass glare: disability glare produced by a head-mounted visual display. *Ophthalmic & Physiological Optics*, 36(2), 167-173.

The link below will direct the reader to this article:

Google Glass Glare.pdf

**BCOVS abstract: Glasgow Caledonian University, September 2013**

**Title: 'The Contrast sensitivity Clock':** Evaluation of a simple test for measuring contrast sensitivity and glare

**Author(s)** Chris Longley, Prof D Whitaker

**Affiliation(s)** University of Bradford

## Abstract

### Background

The role of the optometrist in assessing visual fitness for driving is at a critical juncture. On the one hand we have those that promote the use (and even the relaxation) of a very basic assessment of vision using a number plate. On the other hand we have an amendment to a recent European Union Directive (2009/113/EEC, Brussels 2009) calling for enhanced assessment of driver's visual performance to be carried out at regular intervals by competent clinicians.

### Purpose

One performance measure referred to within the directive is the influence of disability glare on contrast sensitivity. However, the lack of an accepted UK standard measurement technique has led to the UK Department for Transport to reject the relevant parts of the aforementioned directive. This project involves testing a device that hopefully will satisfy this requirement.

### Method

Here we present preliminary data gathered using a novel testing device we term 'The Contrast Sensitivity Clock': a quick, easily understood and highly portable test that involves reading clock wise round a ring of letters, reducing in contrast until they become indistinguishable. This is done firstly without the glare source present and then done again with the glare source.

### Results and Conclusion

We have so far found significant contrast sensitivity differences between groups of patients with and without cataract, indicating this could well be a viable means for assessing contrast sensitivity in practice and thus facilitating the implementation of current EU driving regulations.

Optometry Tomorrow abstract: Brighton, March 2015

**The contrast sensitivity clock: Evaluation of a simple device for measuring contrast sensitivity and glare.**

Mr C Longley[1] Prof D Whitaker[1] and Dr J Heron[1]

Authors affiliations: [1]The University of Bradford.

## Introduction

Disability glare (DG) reduces the contrast of objects making them difficult to see, or sometimes even invisible. This reduction in contrast can largely be attributed to intraocular light scatter and it has been widely documented that the effects of DG are exaggerated as a result of age and even more so with the presence of cataract (van den Berg et al. 2007). Despite previous research identifying a significant association between people with cataract, contrast sensitivity (CS) deficit and crash risk (Owsley and McGwin 2010), CS and glare effects are not routinely tested when assessing one's visual ability to drive. The CS clock is a device that has been developed to try and fill this requirement.

## Method

Binocular CS without glare, CS with glare and DG score were recorded for every participant using the contrast sensitivity clock. The clock involves the use of Sloan letters arranged as the hours on a clock face. These progressively reduce in contrast in a regular fashion as they are read round in a clockwise direction. The letters were mounted onto a high-intensity light box similar to those used in radiography. CS scores were given by the letters correctly identified on each sheet.



Figure 1. Showing an example of the stimuli used for assessing contrast sensitivity with (right) and without (left) glare

In addition to the CS scores, LOCS III cataract grading (un-dilated), habitual VA, a brief case history, iris colour and responses to the visual disability assessment (VDA) questionnaire, distance/lighting/reading subscale were recorded.

**Results**

Data collection on a large scale patient sample (approximately 500 participants) is ongoing. Statistically significant relationships via Mann-Whitney testing have been found for glare score ($z = -5.157$, $p < 0.001$), disability glare score ($z = -5.532$, $p < 0.001$), habitual VA ($z = -5.391$, $p < 0.001$) and participants with and without cataract.

The questionnaire included a question regarding night driving difficulty. A stepwise regression showed that CS with glare score entered at stage one of the analysis and was significantly related to driving difficulty by night $F (1,101) = 19.77$, $p < 0.001$. Habitual VA was found to give no extra information over glare score when predicting perceived driving difficulty by night.

**Conclusion**

The contrast sensitivity clock is a quick and easy device to use. Results thus far show it to be effective at distinguishing how participants with and without cataract and those under and over 60 years of age are influenced by glare. Contrast sensitivity under glare conditions seems to give the most information about perceived driving difficulty at night. Due to these factors, the clock shows promise for future use in the assessment of vision for driving.

**Visual and Physiological Optics- 2nd World meeting, Puebla, 2015**

**Mr C Longley[1] Prof D Whitaker[1]**

Authors affiliations: [1]The University of Bradford.

## Abstract

### Purpose

The Head mounted display (HMD) market is expected to increase in size (approximately 25x) by 2019. Google Glass (Google Inc.) or "Glass" was used to examine the possible reduction in contrast sensitivity (CS) from disability glare, caused by the display screen.

### Methods

CS was measured by way of a sinusoidal contrast grating of 1.7cpd. The background luminance was 106cd/m$^2$ which could then be further reduced with the addition of 0.9 log unit neutral density filters. The orientation of the presented sinusoidal gratings could be oblique right or left, allowing for a two-alternative forced-choice response. CS measurements were recorded for the RE, LE and binocularly with and without Glass.

### Results

In the no glare condition monocular CS was virtually identical in both eyes over all luminance levels. In the binocular condition the expected binocular summation was observed.

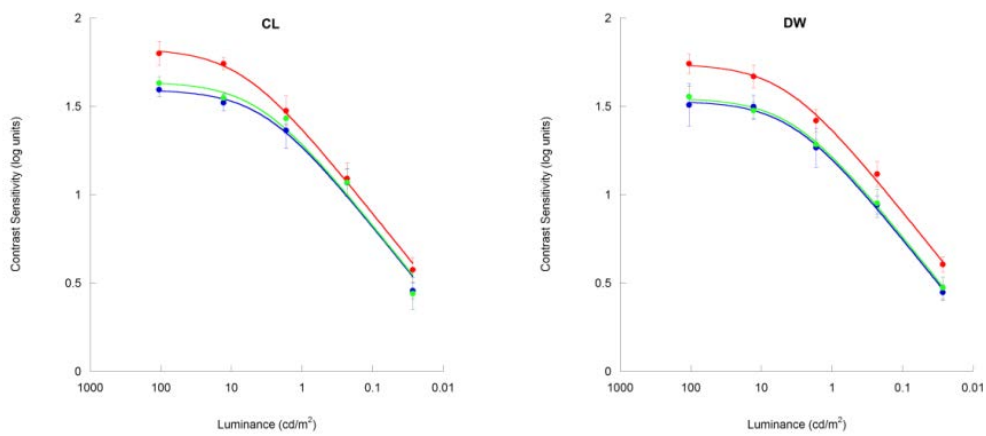


Figure 1 showing the CS for both participants in the no glare condition. The red line shows the binocular performance, the green (RE) and blue (LE) performances respectively

With the Glass in place the effects of binocular summation decreased for both participants as there became a greater difference in monocular CS between the two eyes. Interestingly no binocular inhibition or eye suppression was evident at any luminance level.

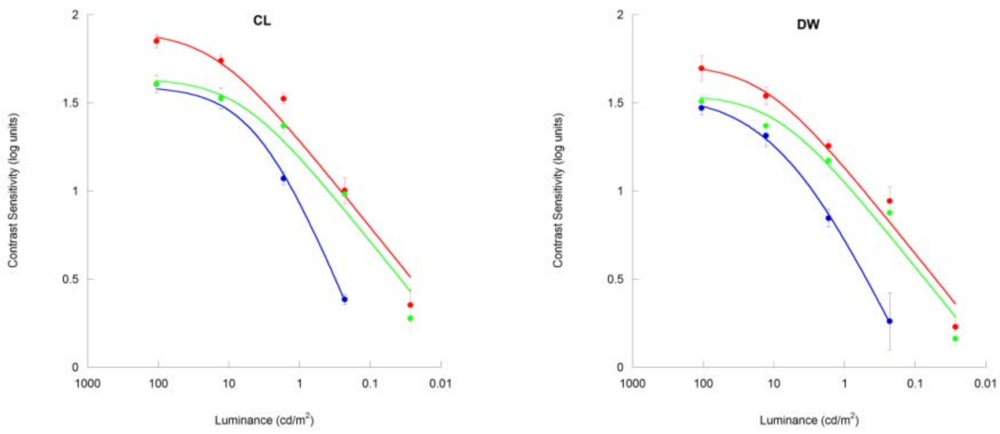


Figure 2 showing the CS data in the glare condition for both participants. The red line shows the binocular CS, green (LE) and blue (RE).

## Conclusions

It is clear from our results that Glass and other such devices are well capable of producing a disability glare effect leading to a reduction in CS from baseline at lower luminance levels. We recommend the wearing of HMD devices in certain situations, an obvious one being driving at night, be advised against until further research takes place.

**BCOVS abstract 2015**

## Google Glass Glare: Disability glare produced by a head mounted visual display

*Chris Longley[*] and Dave Whitaker, Bradford School of Optometry and Vision Science.*

*Abstract*

The use of head mounted display (HMD) systems like Google Glass or “Glass” is projected to rise sharply over the next 10 years. Here we investigate whether the display screen from this type of device might produce disability glare, leading to a reduction in contrast sensitivity (CS).

CS was measured across a wide range of stimulus luminance levels. Glass was situated above the visual axis of the right eye with its display screen activated. CS measures were compared to baseline values without Glass for the right eye, left eye and binocularly. Data were modelled using a combination of established models of neural/quantal noise and intraocular light scatter.

The Glass display screen was found to cause a substantial reduction in contrast sensitivity in the right eye, especially under low luminance conditions. It also caused a small but systematic CS reduction in the left eye most likely due to consensual pupil constriction. With Glass in place there was a reduction in binocular CS due to the loss of binocular summation particularly at lower luminance levels where the performance of each individual eye was most dissimilar. Critically, however, binocular performance never fell below that of the left eye at any stage thereby demonstrating an absence of binocular inhibition.

The display screen of Glass has the potential to significantly reduce the CS in the right eye, particularly under low luminance conditions. It can also have a modest effect on binocular sensitivity by reducing the effects of binocular summation.

*Funded by the College of Optometrists*

## Evaluation of a simple test for measuring contrast sensitivity and glare

Information sheet and consent form

This project is funded by the College of Optometrists and is designed to investigate the effect glare has on the clarity of objects or letters. The project has the aim of producing a test which can assess how well we see under glare conditions in any local opticians practice. This test is particularly interested with finding how glare may affect vision when people are driving, but this test is by no means designed to make any judgment on your own ability to drive.

The test itself involves a clock dial of letters which gradually decrease in contrast as we go around in a clockwise direction. All we ask is that you read the letters until they become too hard to see. This is done twice, the second time with a glare source present which may have some effect on the clarity of the letters seen. The whole test will take less than 5 minutes and the results will be completely anonymous. There is also a very short questionnaire that you will be asked to fill in which asks you how easy you feel certain day to day tasks are. A small amount of information from the eye exam will also be used. Your best corrected vision and also any eye health information which would indicate an expected increase in glare will be noted, such as cataract etc... The results of this test will play no part in the results of your eye exam today.

Participation in this study is completely optional and if there is any part of the test you do not feel comfortable with just let me know and we will stop the test. The test only involves reading letters under the presence of light, no other machinery or drops will be used. The test results will help us to fully understand the effects of glare with a view to hopefully making our roads safer in the future.

Many thanks for taking the time to read this form and if you have any questions feel free to ask.

I am over the age of 18, happy with the details above, and hereby agree to take part in the above study,

Signed:........................................................ Date:.................................

If you have any further questions or queries please feel free to contact me by e-mail: c.i.longley2@student.bradford.ac.uk

## Evaluation of a simple test for measuring contrast sensitivity and glare

Information sheet and consent form

This project is funded by the College of Optometrists and is designed to investigate the effect glare has on the clarity of objects or letters. The project has the aim of producing a test which can assess how well we see under glare conditions in any local opticians practice. This test is particularly interested with finding how glare may affect vision when people are driving, but this test is by no means designed to make any judgment on your own ability to drive.

During this part of the study the reliability of the device will be examined. You will be asked to undertake two separate tests on two separate occasions, separated by at least one week. Both of these visits will require you to read letters of reducing contrast with and without a glare source and take less than 15 minutes to perform. It may be necessary to dilate your eyes during this visit. This is to allow a full ocular assessment to be carried out, in particular assessment of any lens changes (cataract) that may be present. If required the drops will be discussed further and an information leaflet given.

Participation in this study is completely optional and if there is any part of the test you do not feel comfortable with just let me know and we will stop the test. The test results will help us to understand the effects of glare with a view to hopefully making our roads safer in the future.

Many thanks for taking the time to read this form and if you have any questions feel free to ask.

I am over the age of 18, happy with the details above, and hereby agree to take part in the above study,

Signed:....................................................... Date:.................................

If you have any further questions or queries please feel free to contact me by e-mail: c.i.longley2@student.bradford.ac.uk

THE COLLEGE
OF OPTOMETRISTS

Your Optometrist:

Date Issued:

# Tropicamide eye drops

**Tropicamide 0.5% or 1% allows your optometrist to view the inside of your eye more easily by making the pupils wider than normal.**

The drops take about 15 to 30 minutes to work and the effect may last for up to six hours. Occasionally the effect may last until the next day.

**You should not undertake hazardous activities such as driving, cycling or operating heavy machinery while your vision is affected.**

Having large pupils will make you more sensitive to light, especially if it is sunny, and your vision might be slightly blurred.

In the unlikely event that you experience any unusual symptoms such as pain and redness in or around your eyes or your vision seems misty (as though you are looking through a veil or a fogged up window), contact your optometrist or seek medical advice as you might be experiencing an adverse reaction to the drops. Take this note with you.

This leaflet is produced by the College of Optometrists. We are the professional, scientific and examining body for optometry in the UK. People who are our members agree to meet the highest clinical and ethical standards. Look for the letters MCOptom or FCOptom to see if your optometrist is a member.

**Please visit www.lookafteryoureyes.org for more information.**

This leaflet contains general information and it is always best to raise any specific concerns you may have with your optometrist. All our leaflets are thoroughly researched and based on the most up to date scientific evidence. They are reviewed and updated regularly. 

VDA questionnaire, distance/lighting/reading sub-scale:

| To what extent, if at all, does your vision interfere with your ability to' | Not at all | a little | quite a bit | a lot |
|---|---|---|---|---|
| Read? | | | | |
| See in the distance? | | | | |
| Recognise faces across the street? | | | | |
| Watch TV? | | | | |
| See in bright light/glare? | | | | |
| See in poor or dim light? | | | | |
| Drive a car by day? | | | | |
| Drive a car by night? | | | | |